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ENERGY MANEUVERABILITY DISPLAY FOR THE AIR COMBAT MANEUVERING RANGE/TACTICAL TRAINING SYSTEM (ACMR/TACTS)

V. R. Pruitt, W. F. Moroney, and C. Lau

August 1980

NAVAL AEROSPACE MEDICAL RESEARCH LABORATORY
PENSACOLA FLORIDA

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SUMMARY PAGE

THE PROBLEM

Over the past decade, emphasis has been placed on designing fighter aircraft to energy maneuverability criteria. These criteria have indeed increased fighter performance, but they have also presented analysts and pilots with new tasks in fully utilizing this improved capability. In the development of tactics, the energy maneuverability capability of a potential adversary's aircraft must be compared with the maneuvering capability of one's own aircraft. A major factor which determines the outcome of aerial combat is the pilot's ability to maximize the maneuvering capability of his aircraft. This report describes the development of an integrated analog display (turn rate vs calibrated airspeed) for use as a debriefing aid on the Air Combat Maneuvering Range (ACMR).

FINDINGS

The ACMR gathers in-flight data from aircraft while they are engaged in air combat maneuvering. Upon returning from the ACMR, aircrew are presented with 1) a pictorial display of the engagement, and 2) a digital printout of selected encounter paramaters (e.g., velocity, "g", altitude of each aircraft, range between aircraft). The display integrates these relevant energy maneuverability data into an analog format, thus providing an immediate comparison of the performance of each aircraft with respect to the maneuvering envelope of that aircraft and that of the opponent. The display also allows the aircrew to recognize very rapidly whether they are gaining or loosing energy and the rate of gain or loss. The maneuvering envelopes of the F-14, F-4, A-4, and F-5 aircraft can be displayed in this dynamic format. It is expected that this new format 1) will provide a better means for pilots to determine how well they have maximized the performance of their aircraft, and 2) may serve as an aid in tactics development.

A brief discussion of the nature of energy maneuverability is contained in an Appendix.

RECOMMENDATIONS

It is proposed that the effectiveness of the energy maneuverability (EM) display and the companion instructional video tape should be evaluated. The potential incorporation of the display into other ACMRs/ACMIs and ACM simulators should also be considered.

ACKNOWLEDGMENTS

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I. INTRODUCTION

Over the past decade, emphasis has been placed on designing fighter aircraft to energy maneuverability criteria. While this emphasis has resulted in fighter aircraft with improved performance capability, it has presented analysts and pilots with new tasks in fully utilizing this improved capability. In the development of tactics, the energy maneuverability capability of a potential adversary's aircraft must be compared with the maneuvering capability of one's own aircraft. A major factor which determines the outcome of aerial combat is the pilot's ability to maximize the maneuvering capability of his aircraft.

Before discussing energy maneuverability (EM) the distinction between energy management and energy maneuverability must be considered. Pruitt (1) makes the following distinction:

- Energy Management - relates to the use of potential and kinetic energy, and stored energy from fuel, to maximize or optimize the total weapon system to achieve the desired task.

- Energy Maneuverability - is the analysis of maneuverability (the ability to perform a change, or a combination of changes, in direction, altitude, and airspeed) expressed in terms of energy and energy rate.

Thus, energy maneuverability is not directly concerned with fuel consumption. Indeed, within the framework of these definitions, it would be possible for a pilot to perform poorly on energy management by exhausting his fuel supply, while using appropriate or inappropriate energy maneuverability tactics. However, as we shall see. use of appropriate energy maneuverability tactics can result in reduced fuel consumption.

During the 1975 Advanced Aircrew Display Symposium (2) RADM J. S. Christiansen, USN (Ret.), then the Assistant Deputy Chief of Naval Operations, Air Warfare, addressed the needs of fighter pilots. He stated, "As a fighter pilot . . . I want to know how much (aircraft performance) I've got left and I need it (the information) where I can see it." The need for information on how well the aircraft's maneuvering capability has been utilized was a topic of considerable discussion at the 1976 Navy Fighter Weapons Symposium (3).

Some specific requirements for EM data include:

1) <u>Flight Safety</u>. The Commanding Officer of the Naval Safety Center reported (4) that during the period from July 1969 to April 1974, forty-two naval aircraft were destroyed, 8 aircraft were damaged, and 27 deaths were attributable to the lack of integrated V-N (velocity-"g") envelope information. A review (5) of USAF and Navy accidents involving unrecoverable loss of control revealed that between April 1972 and March 1976, 92 aircraft were lost due to stall/spin departures. Forty of the 92 aircraft lost were F-4s. These losses did not include any loss due to mechanical failure. The accident summary usually listed the pilot as the primary cause and contained a statement such as "Pilot allowed himself to get into a position from which he could not recover."

The quality fighter/attack pilot is an individual who is one with his machine, i.e., he integrates altitude, "g", airspeed, angle of attack with the feel and sounds of the aircraft. He creates, in his head, the V-N diagram (which describes the performance capability of an aircraft in terms of load factor "g" and velocity) or parts of the V-N diagram and, as accurately as possible, locates his aircraft in that diagram. Efforts have been made to present V-N information to pilots but, in most cases, the displays did not progress beyond the simulator stage or, if they were flown, they were flown only experimentally. At present, no integrated V-N information is displayed to the pilot aboard operational USAF or Navy aircraft, nor is any integrated information displayed for use during debriefings on the Air Combat Maneuvering Range (ACMR). Techniques for displaying energy maneuverability data in flight will not be discussed in this report, interested readers are directed to Stanley (6) and Moroney and Barnette (5).

2) Differences in Present and New Generation Fighters. Because of the high thrust to weight ratios and the low wing loadings of the new generation of fighters, in particular the F-16 and the F-18, tomorrow's fighter/attack pilot can gain or lose energy at a much faster rate than he could with present operational aircraft. Pilots of this new generation of aircraft will need to learn that, at high speeds, keeping the throttle full forward during air combat maneuvering (ACM) will prevent them from achieving their tightest turn. The evolution of strakes, slots, and lifting body fuselages provides much more subtle cues of aircraft performance than are available with today's aircraft. Because of the subtle nature of these cues, we can expect the new generation of fighter/attack aircraft to be inadvertently over-stressed and/or their capability not maximimized in ACM.

3) Differences in Aircrews. In ACM the requirement is eyes-out-of-the cockpit with a rare glance inside until the target is off the nose. The F-4 pilot has a Radar Intercept Officer (RIO) or Guy-in-Back (GIB) to provide altitude/airspeed and weapon status information when needed. However, pilots of future fighters will be flying single seat aircraft. Thus, the pilot's need for performance information is increasing while the sources of such information are decreasing.

4) Limited Training Opportunities. Increased fuel/maintenance costs have increased training cost; thus, today's fighter/attack pilot can expect less "seat-of-the-pants" experience in ACM and weapon delivery. For ACMR to be truly cost-effective maximum utilization must be made of the data collected in flight.

5) Lack of Energy Maneuverability Training During Pilot Training. While acknowledging the importance of energy maneuverability (EM), most pilot training does not address it for a variety of reasons, including the technical nature of the topic, other syllabus requirements, and the inability of many instructor pilots to define the envelope for themselves, much less for students. An exception to this deficiency is the EM course taught at the Naval Fighter Weapons School. These lectures provide a basis for tactics development and are followed up with in-flight demonstrations to reinforce the lectures. Additionally, EM is routinely discussed during the debrief.

6) Tactics Development. While an actual air combat encounter lasts only a few minutes, considerable preparation must precede the encounter. A prerequisite for a successful or at least neutral encounter is knowledge of the maneuvering capability of both the friendly and adversary aircraft. Prior to any encounter a pilot must compare his energy maneuverability with that of a potential adversary. Armed with this knowledge the pilot can then develop tactics which favor his aircraft and which may force his adversary to fly in a regime where the adversary aircraft has less capability.

For the above reasons an effort was undertaken to develop an EM display for use on the ACMR. Such a display could use data presently down-linked and reformat it so as to allow aircrew to view their EM performance and compare it with that of their adversary. Prior to describing the development of such a display it would be appropriate to discuss how EM is utilized in ACM. Air combat is characterized by a highly dynamic maneuvering environment against a nonpredictable aggressive adversary. This arena involves three prime combat situations for one vs one combat: defensive, neutral, and offensive.

a. Defensive

The prime objective for the pilot on the defensive is that of remaining out of the adversary's cone of fire. The pilot can accomplish this either by turning faster or by turning inside of his opponent. This is where the pilot's knowledge of his maneuvering capability relative to his adversary is required. If the defensive pilot has too much energy, his maneuvering capability is seriously hampered, both in terms of altitude and airspeed. On the other hand, if the defensive pilot remains at too low an energy level maneuvering performance is again hampered and, even worse, the pilot will probably not be given an opportunity to regain lost energy. The defensive combat role is generally characterized by a series of energy loss maneuvers, because maximum maneuvering performance occurs at corner velocity, the point of maximum energy loss.

While gaining energy would be useful for increasing maneuvering potential, the adversary would most certainly welcome the defensive pilot's mistake of unloading just for the sake of energy gain. On defense the pilot will either force an overshoot by losing energy faster than the adversary, or increase the adversary's bearing angle to a point where an energy gain maneuver might be accomplished.

As one would expect, during close-in combat the energy levels of both aircraft are reasonably close together, with the defender setting the pace. If the attacker possesses too much energy, he is leaving himself open to a disastrous overshoot. If the attacker does not possess enough energy, the target will soon out-turn the attacker. Today's pilot must account for these factors by relating visual inputs to his training and experience. With the advent of aircraft having greater thrust to weight ratios and lower wing loading, these airplanes are able to gain and lose energy at faster rates than ever before. The area of maneuver display technology is lagging behind these greater maneuvering capabilities. In order for the pilot to exploit the aircraft's performance to the maximum, he must at all times be aware of his relative maneuver conditions and capabilities, and know where his best capabilities can be realized.

b. Neutral

The neutral situation is a near standoff where neither airplane can easily gain a positional advantage. To break the stalemate one pilot must either capitalize on the other's mistake or utilize his maneuvering capability to change the situation. In this situation discretion may be the better part of valor, and the pilot may choose to unload and gain energy for separation. On the other hand, the pilot may choose to exercise a vertical plane maneuver (trading airspeed for altitude), like a yo-yo, to reduce bearing by decreasing his effective turn radius in his adversary's turning plane. As was the case for the defensive airplane, the pilot can be provided valuable information about the energy consequences of each maneuver to assist in his decision making.

c. Offensive

To perform offensive, aggressive combat, positional advantage must be achieved and maintained. The pilot must manage his energy if he is to maintain his positional advantage. On the offensive, the chief objective of energy management is to maintain the proper use of energy gain-energy loss maneuvers relative to the adversary. In an offensive engagement (other than a hit and run) with excessive energy, the adversary will attempt to force an overshoot or force the attacked to lose too much energy. So, for the pilot on the offensive, energy management is necessary for achieving and maintaining good positional advantage for subsequent tracking tasks.

II. DEVELOPMENT OF THE EM DISPLAY

Traditionally, V-N diagrams ("g" vs velocity) have been used to describe an aircraft's capabilities and limitations and/or to compare the performance capability of two aircraft. Another method which has been used for these purposes is turn rate vs velocity. This rate-velocity format provides a simple method for developing tactics that can be explained in terms of the single parameter: velocity. An additional method is through Altitude-Mach (H-M) diagrams. These diagrams usually indicate where one aircraft has a specific excess energy (P_s) or "g" advantage with respect to the other. However, the data, while useful in designing aircraft, are difficult to interpret and even more difficult to evaluate in nonengineering applications. Some of the difficulties associated with the H-M diagrams were documented by Pruitt (7).

Since the H-M diagram was considered inappropriate, the other two energy management displays were developed with the intention of comparing their suitability for use with the Display and Debrief Subsystem (DDS) of the ACMR. The DDS of the ACMR provides the means to review flight data and analyze individual maneuvers or engagements. The addition of EM displays to the DDS provides the pilots with information that can be used to qualitatively evaluate individual performance. McDonnell Aircraft Company (MCAIR) was awarded a contract in September 1978 to develop these display concepts for possible incorporation into the ACMR. Eventually, a variant on the turn rate vs velocity profile - the maneuver triangle - was selected for incorporation into the ACMR. The turn-rate vs velocity profile will be discussed first followed by the maneuver triangle, the V-N profile, and finally the ACMR EM Display. Readers who may not be familiar with some of the underlying concepts of EM may wish to refer to Appendix A.

2.1 TURN RATE-VELOCITY PROFILE

The turn rate-velocity profile is shown in Figure 1. The left side of the large cone shape represents the aircraft maximum lift limit, or $C_{L_{max}}$. The right side represents the aircraft structural limit, or specified maximum load factor. For any given velocity, these boundaries represent the maximum turn rate available. "Corner turn" is defined as the point where the maximum lift limit intersects the structural limit. The corner turn point exhibits the highest turn rate possible. The corner velocity, then, is the speed at which the corner turn exists.

Below the maximum limit boundaries, lines of constant P_s (in ft/sec) can be shown, indicating the specific energy loss and gain rates for the aircraft. The $P_s = 0$ line represents the sustained turn rate. The point where the sustained turn rate line peaks represents the velocity for the aircraft's maximum sustained turn.

The area above the sustained turn rate line represents an area of energy loss, or areas where bleed rates (deceleration) build to a maximum. The maximum loss occurs at the corner turn. Maximum acceleration occurs where P_s is a maximum, along the base at zero turn rate.

Figure 2 shows the rate-velocity profile for an F-4J weighing 39,259 pounds at 10,000 feet. The velocity band for maximum bleed rates (negative P_s) and maximum accelerations (positive P_s) can be easily determined.

These data are valuable for examining individual aircraft performance, but are of little value in determining how to use the aircraft against a specific threat. This information is obtained by overlaying the rate-velocity profiles for both aircraft.

Figure 3 is a profile of an F-4J and Threat A. When the F-4 is slower than 450 KCAS, the threat aircraft has a clear turn rate advantage. However, the F-4 can out-accelerate the threat and the best F-4 acceleration advantage occurs between 375-575 KCAS. Also, if the F-4 and the threat fly sustained turns above 500 KCAS, the threat will be in an energy loss region if the threat tries to turn with the F-4. The pilot of the F-4 must therefore be careful not to let his airspeed decrease below 450 KCAS. Since the F-4 has a higher P_s at the lower turn rates, it has a superior climb rate advantage over the threat. (P_s is also a measure of steady state rate of climb.) This would imply that a useful tactic is to climb if the threat becomes slow, since the F-4 has the capability to gain energy faster. The turn rate-velocity is thus a valuable tool. When properly used, it can be valuable in developing ACM tactics to exploit strengths and weaknesses.

The significant points in the turn rate-velocity plot are shown in Figure 4. The displays are designed to relate maximum maneuvering performance. Therefore, all data represent maximum power settings. For $P_s = 0$ calculations, drag due to lift ("g") is increased until the drag is equal to the thrust.

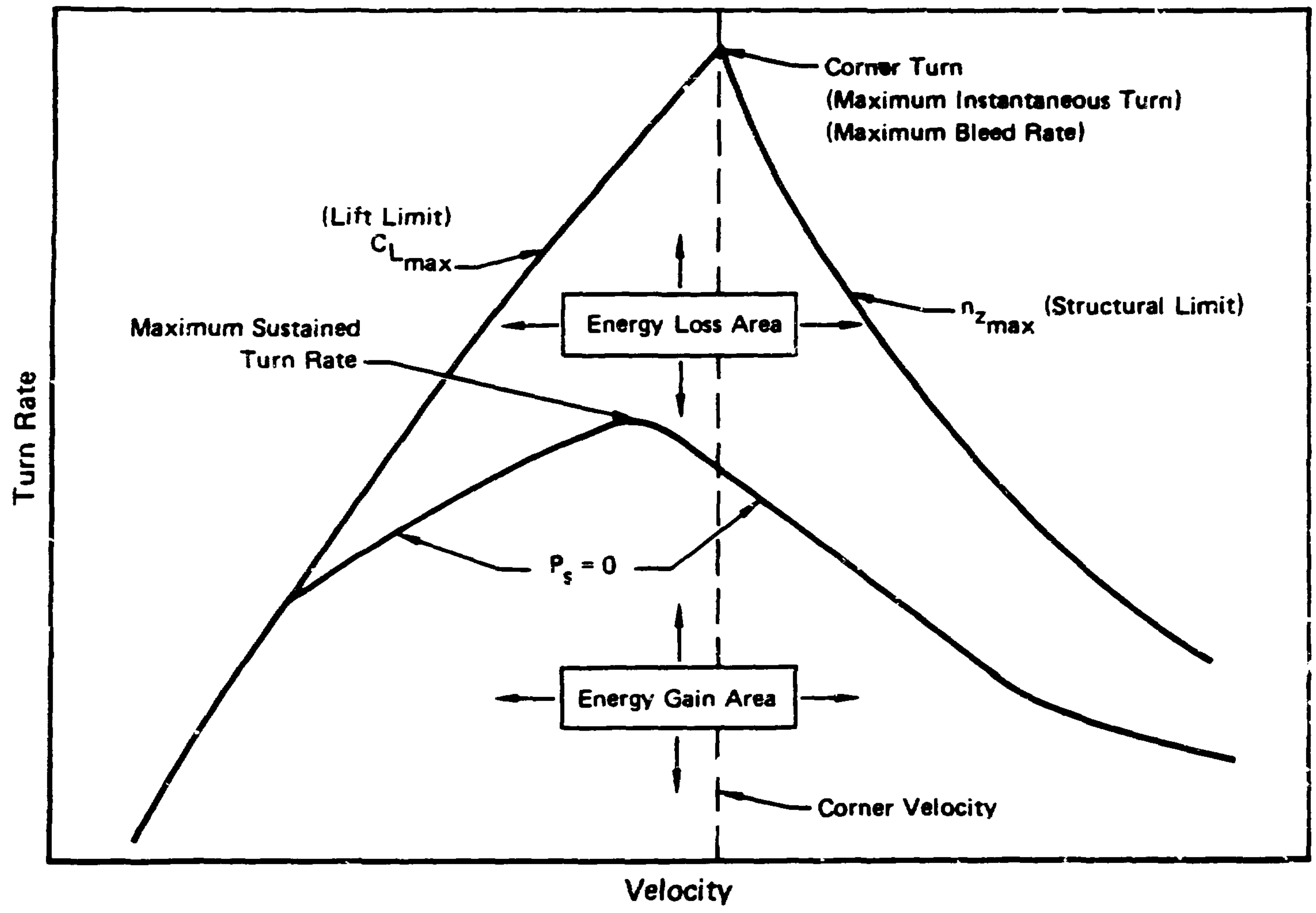


Figure 1. Rate Velocity Profile

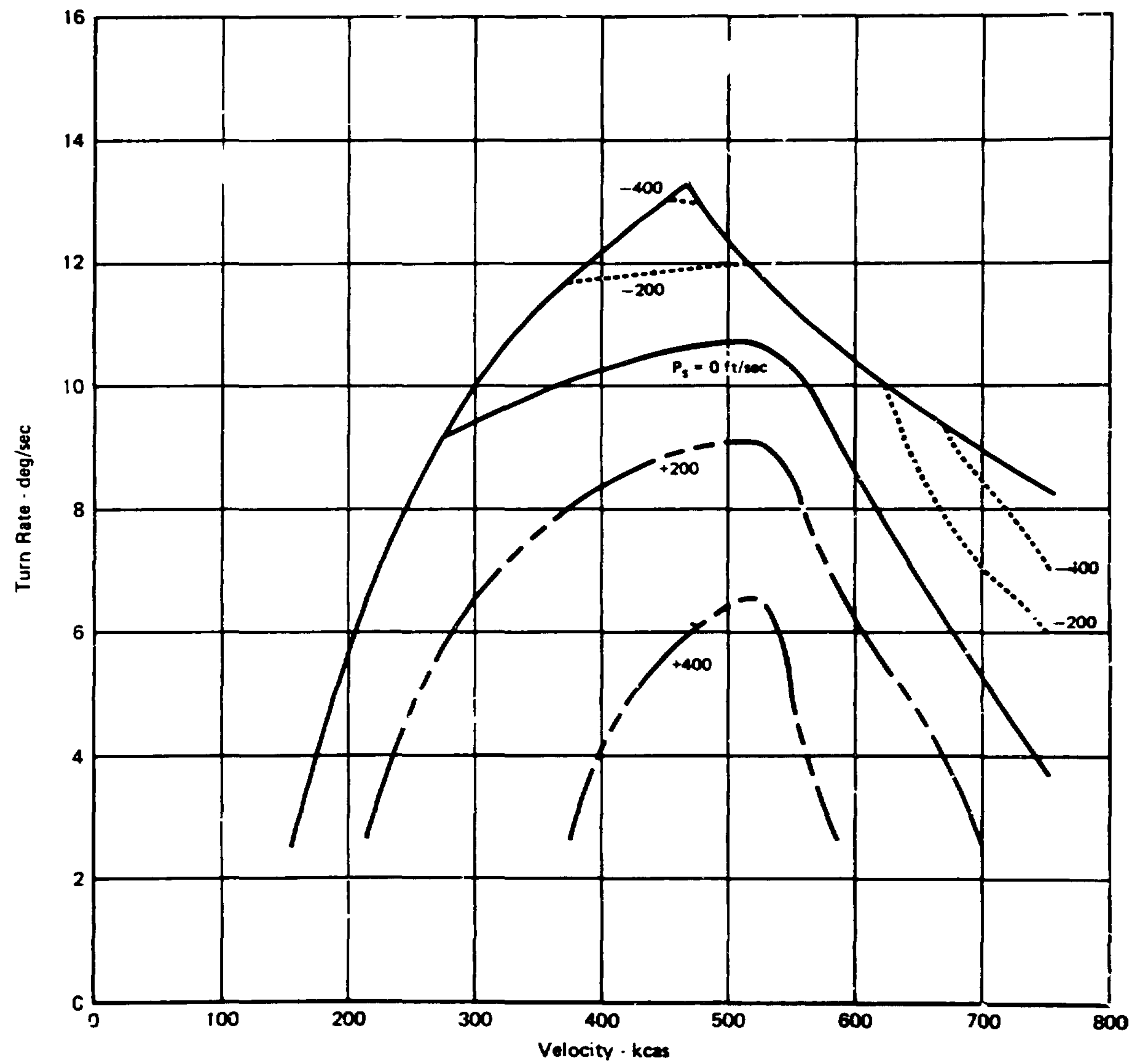


Figure 2. Turn Rate vs Velocity
F-4 Altitude = 10,000 ft

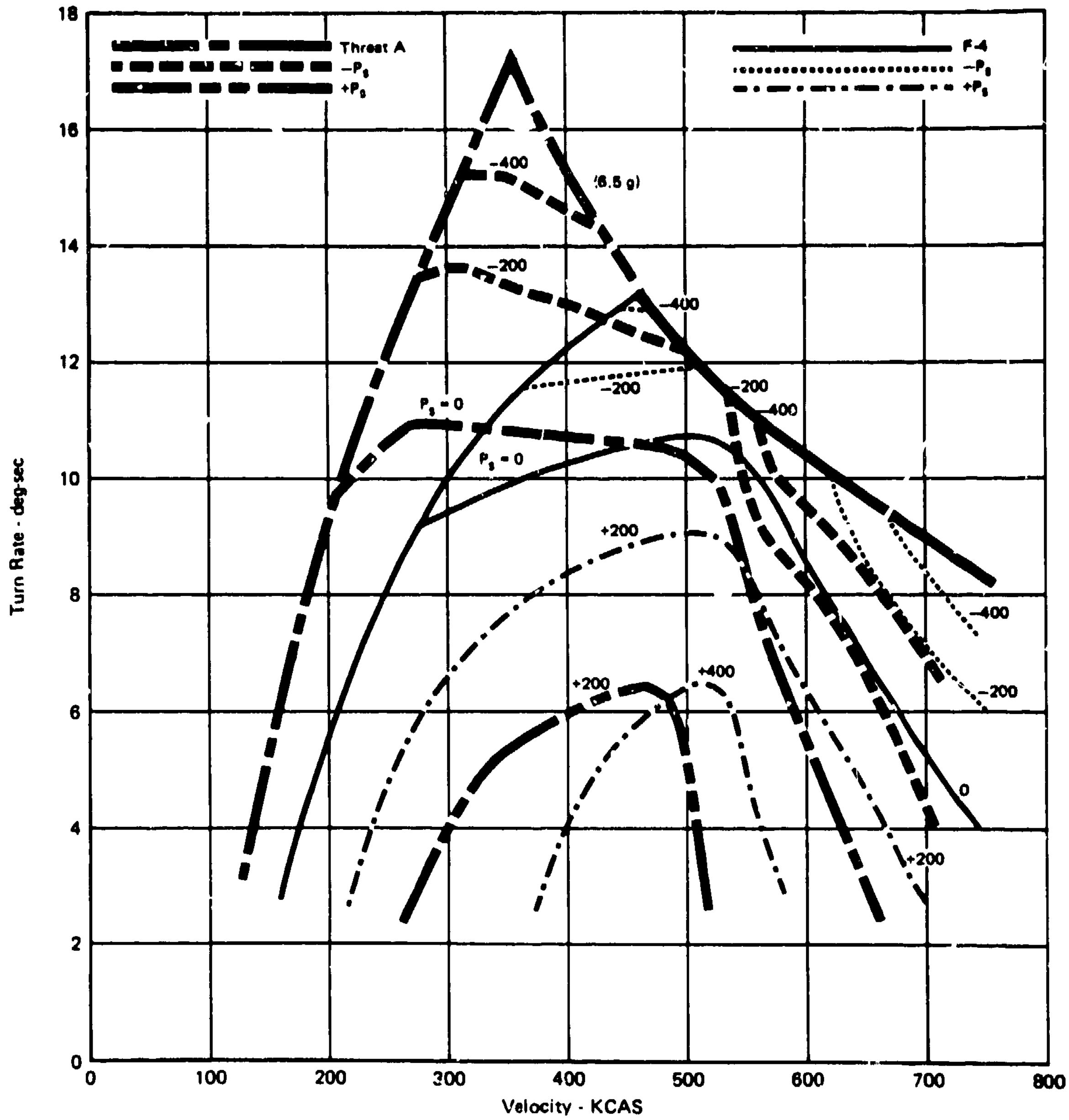
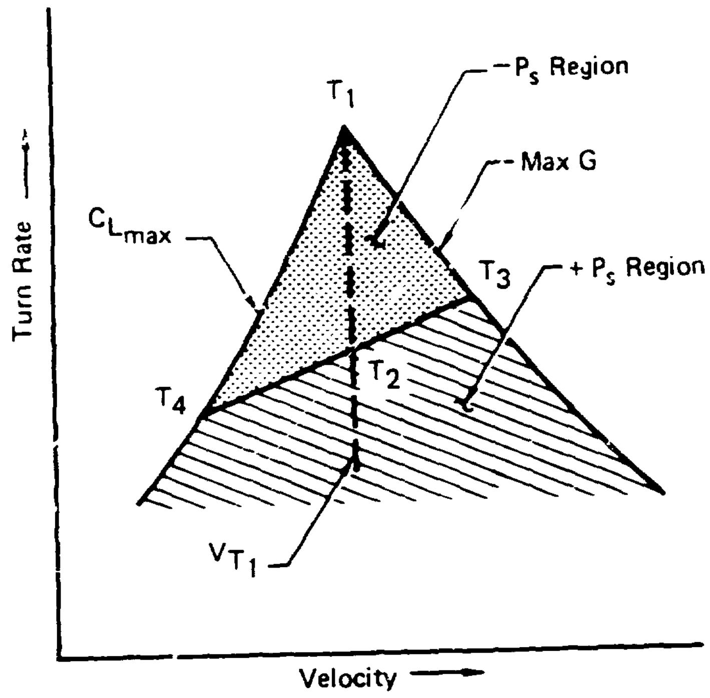


Figure 3. Turn Rate vs Velocity
Threat A vs F-4
Altitude = 10,000 ft



T_1 **Maximum Rate Turn**
- Maximum Rate of Turn
- Near Minimum Turn Radius
- Airplane Decelerating

T_2 **Steady State at Maximum Turn Rate Velocity**
- Maximum Instantaneous Turn Capability Available
- Thrust, Drag and Weight are Balanced

T_3 **Steady State Maximum Rate of Turn**
- Maximum Sustainable Rate of Turn
- Maximum Load Factor
- Thrust, Drag and Weight are Balanced

T_4 **Steady State Minimum Radius of Turn**
- Minimum Sustainable Turn Radius
- Thrust, Drag and Weight Balanced

Figure 4 Key Turning Conditions on Rate-Velocity Diagram

- Point T_1 represents the quickest-tightest turn (corner turn), and as stated previously, occurs at the intersection of the maximum structural limit boundary.

- Point T_2 represents the steady state turn at the corner velocity. This is a thrust=drag condition and speed where the quickest-tightest turn is available if needed.

- Point T_3 represents the maximum steady state turn.

- Point T_4 represents the minimum sustained turn radius. Depending upon the aircraft's thrust-to-weight ratio turns may or may not be sustained below this airspeed. The area to the left of the T_4 velocity represents an area of low "g" and minimum turning capability, and should be avoided during ACM operations, unless a vertical maneuver tactic so dictates.

2.2 MANEUVER TRIANGLE

The baseline maneuver triangle is the basic EM display developed and used by MCAIR (1). It is a simplification of the turn rate-velocity profile, showing the maximum limits and the $P_s = 0$ line. On the original maneuver triangle the vertical scale had been normalized to a height of 260 display units. Regardless of altitude, the apex remained fixed and represented the current maximum available instantaneous turn rate. The horizontal scale was fixed at 300 display units and represented the aircraft's V_{max} for the current altitude. During altitude changes, the corner turn point shifted laterally as a result of the horizontal scale factor changes.

Figure 5 represents the F-4's maneuver triangle for 5000 feet increments between sea level and 40,000 feet. The maneuver triangle for each subsequent altitude is scaled, based on the maximum turn rate (corner turn) at sea level. From this figure, one can visualize the dynamics of the display as altitude is varied.

When initially mechanized on the West Coast ACMR, the display appeared as shown in Figure 6. This panel represents data for two aircraft, the Maneuver Triangle being for aircraft 1. The small symbol "1" on the display shows the current state within the current envelope. The small number "2" on the display represents the current turn rate and velocity of the second aircraft. The lower portion of the display is the digital display of the parameters shown presently on the DDS "flight display."

P_s, $\dot{V}$ and $\dot{H}$ were added to show energy rate and the two basic parameters that contribute to it.

Figure 7 defines the points used to generate the data on the Display and Debrief Subsystem (DDS). The variables are defined as follows:

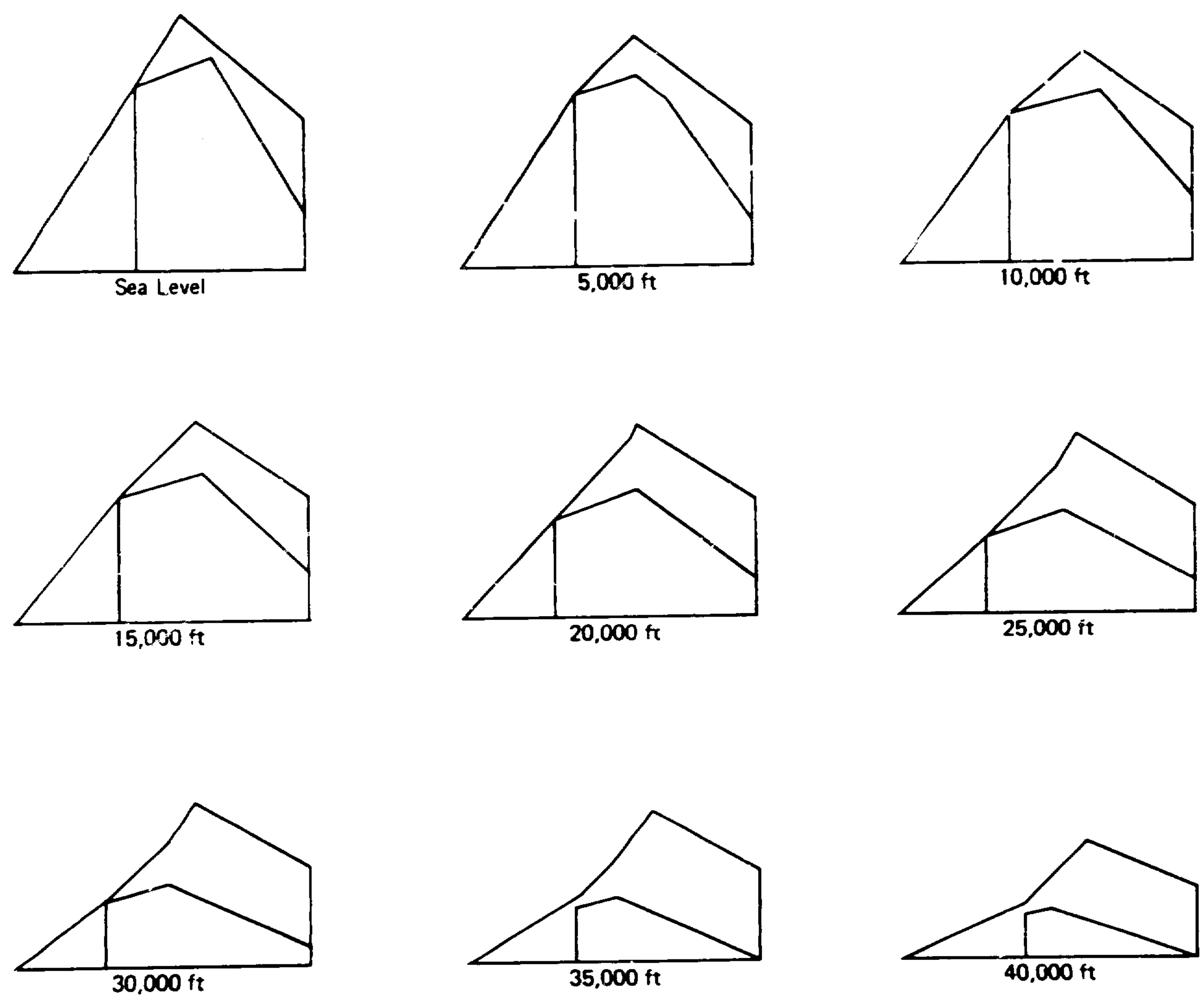


Figure 5. Maneuver Triangle
Sea Level to 40,000 ft
F-4 Gross Weight = 39,259

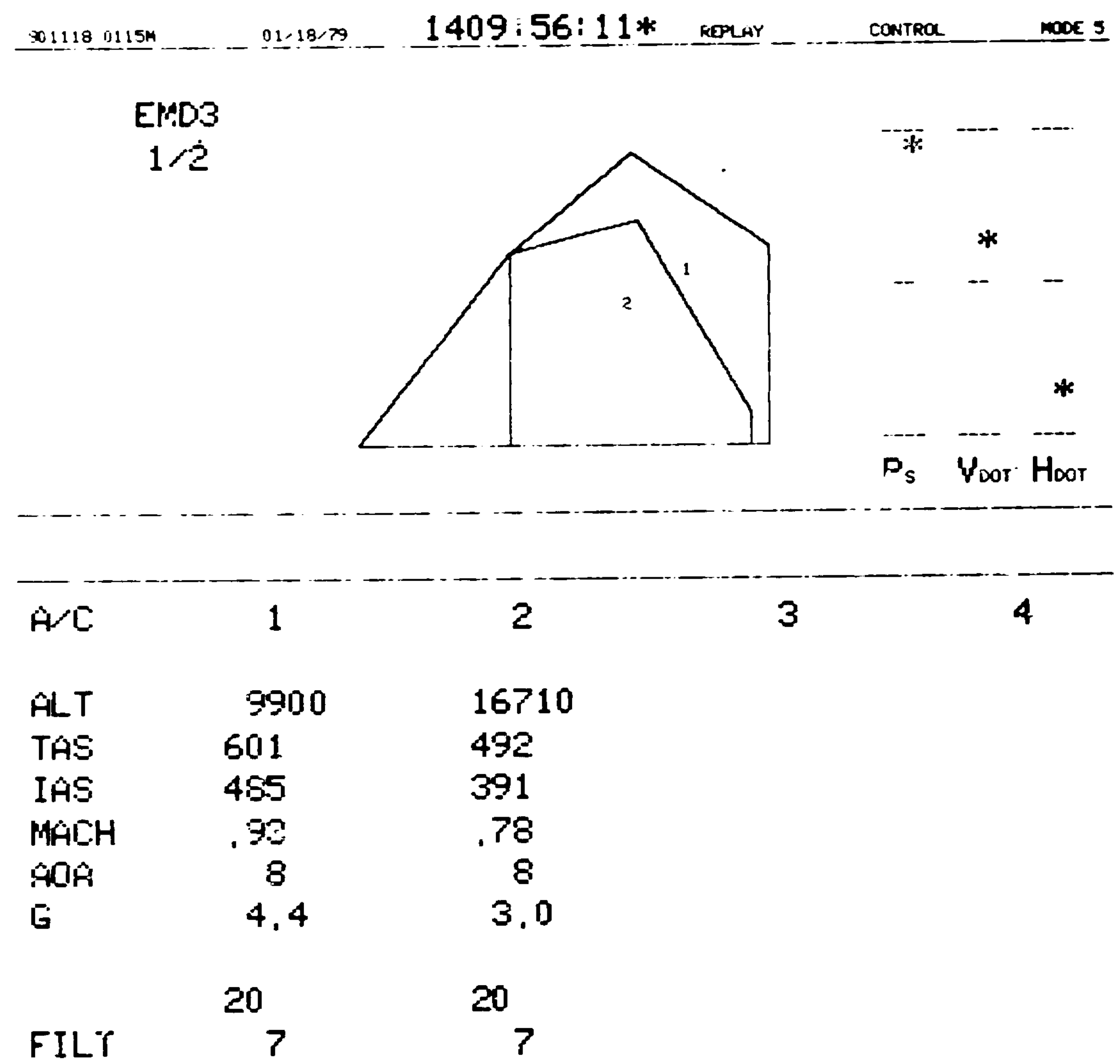


Figure 6. DDS GRAPHICS
Maneuver Triangle Format

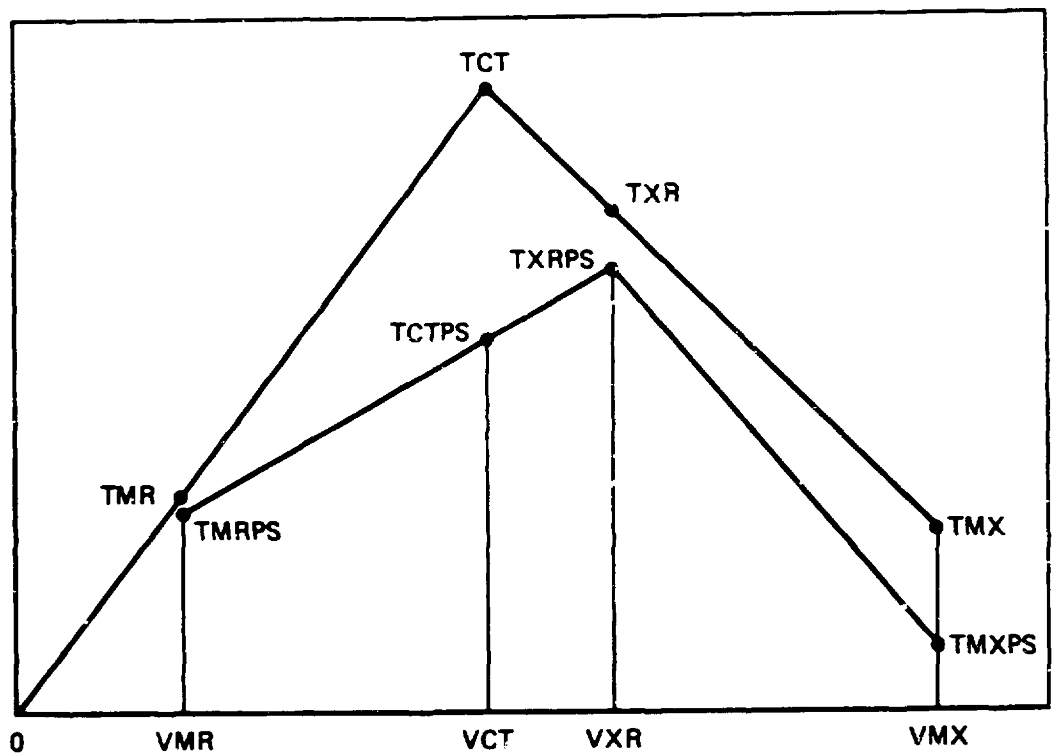


Figure 7. Display Data Point Definition, Maneuver Triangle

VMR = Velocity for the minimum sustained turn radius at specified fuel, specified altitudes.

TMR = Maximum horizontal turn rate at VMR.

TMRPS = Sustained turn rate at VMR.

VCT = Corner velocity - velocity for maximum instantaneous turn rate at specified fuel, specified altitude.

TCT = Maximum horizontal turn rate at VCT.

TCTPS = Sustained turn rate at VCT.

VXR = Velocity for maximum sustained turn rate at specified fuel, specified altitude.

TXR = Maximum horizontal turn rate at VXR at specified fuel, specified altitude.

TXRPS = Maximum sustained turn rate occurs at VXR.

VMX = 750 KCAS, or actual V_{max} if less than 750 KCAS.

TMXPS = Sustained turn rate at VMX.

The units of all velocities are in ft/sec and all turn rates are in deg/sec. To provide sufficient data for subsequent construction of the display on the DDS graphics, data for nine altitudes, sea level to 40,000 feet, were generated. Tables I-IV represent the data necessary to generate the displays for two F-4 configurations flying out of Miramar and Yuma. The 5,000-foot altitude increments have been found to provide adequate interpolation intervals between data points.

For data computation at intermediate altitudes, linear interpolation is performed for each point defined on Figure 7. The result of the interpolation between two table altitudes is the data that are used for subsequent display. Prior to use for final display at any specified altitude the data are scaled based upon the maximum sea level turn rate.

The data are generated by using a MCAIR-developed computer program that balances thrust and drag as a function of "g" and airspeed to determine the various turn parameters for specified P_s levels. Each set of data is calculated at a specified constant gross weight.

2.3 V-N DIAGRAM

A display in the shape of a V-N diagram was also mechanized. A major difference between this and a conventional V-N diagram is that the $P_s = 0$ line is generated using maximum sustained turn rates in lieu of maximum sustained load

Table I

F-4 GW = 39,259 lb (Miramar)
No Tanks, 1 - AIS Pod, 1 - AIM9

```
F-4   GW=39259 LBS   (MIRAMAR)
  NO TANKS,1-AIS POD, 1-AIM9

DATA VMR/309.,294.,277.,259.,238.,220.,221.,281.,325./
DATA VXR/504.,527.,513.,477.,433.,400.,369.,380.,380./
DATA VCT/429.,451.,465.,460.,453.,453.,448.,479.,479./
DATA VMX/9*750./
DATA TMR/12.52,10.80,9.22,7.63,6.20,4.80,4.21,4.03,3.56/
DATA TMRPS/12.2,10.78,9.21,7.62,6.18,4.79,3.87,3.47,2.78/
DATA TXR/13.92,12.55,12.12,12.14,11.09,9.17,7.62,6.40,4.37/
DATA TXRPS/13.79,10.62,10.73,9.19,7.81,6.46,5.29,4.17,3.08/
DATA TCT/16.35,14.63,13.33,12.56,11.85,11.14,10.54,9.66,7.51/
DATA TCTPS/13.37,12.01,10.58,9.16,7.79,5.94,4.50,3.23,2.46/
DATA TMX/9.33,8.85,8.31,7.80,7.29,6.80,6.27,5.97,4.64/
DATA TMXPS/3.29,2.59,3.83,3.00,2.44,2.00,1.09,0.,0./
```

Table II

F-4 GW = 39,754 lb (Yuma)
No Tanks, 1 - AIS Pod, 1 - AIM9

```
F-4   GW=39754 LBS   (YUMA)
  NO TANKS,1-AIS POD, 1-AIM9

DATA VMR/309.,294.,277.,259.,238.,220.,222.,289.,327./
DATA VXR/505.,538.,513.,477.,433.,402.,370.,380.,380./
DATA VCT/433.,455.,467.,463.,455.,455.,450.,479.,479./
DATA VMX/9*750./
DATA TMR/12.35,10.65,9.09,7.51,6.09,4.71,4.15,4.05,3.54/
DATA TMRPS/12.34,10.63,9.08,7.50,6.08,4.70,3.81,3.49,2.74/
DATA TXR/13.90,12.31,12.12,12.14,10.95,9.09,7.53,6.31,4.73/
DATA TXRPS/13.61,12.19,10.59,9.07,7.71,6.38,5.21,4.10,3.03/
DATA TCT/16.20,14.51,13.36,12.49,11.78,11.10,10.49,9.53,7.41/
DATA TCTPS/13.23,11.86,10.45,9.05,7.67,5.83,4.40,3.18,2.42/
DATA TMX/9.32,8.83,8.31,7.83,7.28,6.79,6.29,5.88,4.58/
DATA TMXPS/3.00,2.47,3.73,3.00,2.37,2.00,1.00,0.,0./
```

Table III

F-4 GW = 41,063 lb (Miramar)
Centerline Tank, 1 - AIS Pod, 1 - AIM9

```
F-4   GW=41063 LBS   (MIRAMAR)
  CL. TANK,1-AIS POD, 1-AIM9

DATA VMR/307.,292.,274.,267.,236.,219.,231.,305.,338./
DATA VXR/527.,543.,510.,465.,421.,395.,369.,369.,374./
DATA VCT/443.,466.,474.,469.,461.,461.,455.,479.,479./
DATA VMX/9*750./
DATA TMR/11.87,10.21,8.68,7.16,5.78,4.41,4.18,4.05,3.65/
DATA TMRPS/11.87,10.19,8.86,7.15,5.76,4.40,3.773,3.47,2.64/
DATA TXR/13.31,12.19,12.20,12.22,10.17,8.59,7.25,5.80,4.49/
DATA TXRPS/13.15,11.68,10.12,8.66,7.35,6.06,4.93,3.85,2.80/
DATA TCT/15.86,14.17,13.09,12.34,11.63,10.98,10.38,9.22,7.16/
DATA TCTPS/12.77,11.38,10.02,8.65,7.02,5.19,3.72,2.70,2.01/
DATA TMX/9.35,8.85,8.30,7.85,7.32,6.80,6.28,5.70,4.42/
DATA TMXPS/9*0./
```

Table IV

F-4 GW = 40,583 lb (Yuma)
Centerline Tank, 1 - AIS Pod, 1 - AIM9

```
F-4  GW=40583 LBS   (YUMA)
 CL. TANK.,1-AIS POD, 1-AIM9

DATA UMR/30[illegible].,292.,274.,257.,236.,219.,225.,304.,331./
DATA UXR/527.,543.,510.,465.,421.,395.,369.,369.,374./
DATA UCT/441.,464.,472.,467.,460.,460.,455.,479.,479./
DATA UMX/9*750./
DATA TMR/11.95,10.28,8.75,7.21,5.82,4.46,4.07,4.07,3.51/
DATA TMRPS/11.95,10.26,8.74,7.20,5.81,4.45,3.66,3.49,2.61/
DATA TXR/13.31,12.18,12.10,12.29,10.22,8.62,7.30,5.84.4.51/
DATA TXRPS/13.23,11.75,10.19,8.71,7.40,6.10,4.97,3.88,2.82/
DATA TCT/15.93,14.22,13.12,12.36,11.66,11.00,10.40,9.23,7.21/
DATA TCTPS/12.84,11.45,10.08,8.71,7.10,5.24,3.76,2.72,2.03/
DATA TMX/9.29,8.82,9.28,7.81,7.26,6.80,6.28,5.74,4.45/
DATA TMXPS/9*0./
```

factor. If actual maximum sutained "g" were displayed, the pilot would be supplied with incorrect velocity information. For example, an F-4 weighing 39,259 pounds at 10,000 feet reaches maximum sustaining "g" at 546 KCAS. The maximum sustained turn rate occurs at 513 KCAS. The sustained turn rate at maximum sustained "g" is lower than the maximum sustained turn rate and the turn radius is approximately 700 feet larger. Velocity data obtained from a turn rate-velocity profile in a classroom could not be correlated unless this display change were made. Turn rate is converted into "g" by using the following expression:

$$g = \sqrt{(\theta * V/1845.06)^2 + 1}$$

where: θ = turn rate (deg/sec)

V = velocity (ft/sec) TAS

The associated display diagram is shown in Figure 8,

where:

VNTRM = SQRT ((TMR * VMR/1845.06)^2 + 1)

VNTMRPS = SQRT ((TMRPS * VMR/1845.06)^2 + 1)

VNTXRPS = SQRT ((TXRPS * VXR/1845.06)^2 + 1)

VNTCT = SQRT ((TCT * VCT/1485.06)^2 + 1)

VNTCTPS = SQRT ((TCTPS * VCT/1845.06)^2 + 1)

VNTMX = SQRT ((TMX * VMX/1845.06)^2 + 1)

VNTMXPS= SQRT ((TMXPS * VMC/1845.06)^2 + 1)

VNTXR + SQRT ((TXR * VMR/1845.06)^2 + 1)

Figures 9 through 11 show the V-N diagram for an F-4 at 41,500 pounds using various vertical scale factors. The vertical scale of 150 units was selected since it more closely represented the classical shape of a V-N diagram. The horizontal scale remained at 300 units.

Figure 12 represents the V-N diagram as it appears on the ACMR DDS scope. Using the points calculated from the above equations, the data may be used directly if zero "g" is used as a base. Since the area between zero "g" and 1 "g" is of no value, the base of the V-N diagram has been adjusted to a base of 1 "g". A base of zero was used; however, unity was subtracted from all load factors prior to the final display plot. This technique allows the use of the additional area for display. V and H had not been added when this frame was taken. The information on the lower portion of the display is the same as for the rate-velocity display.

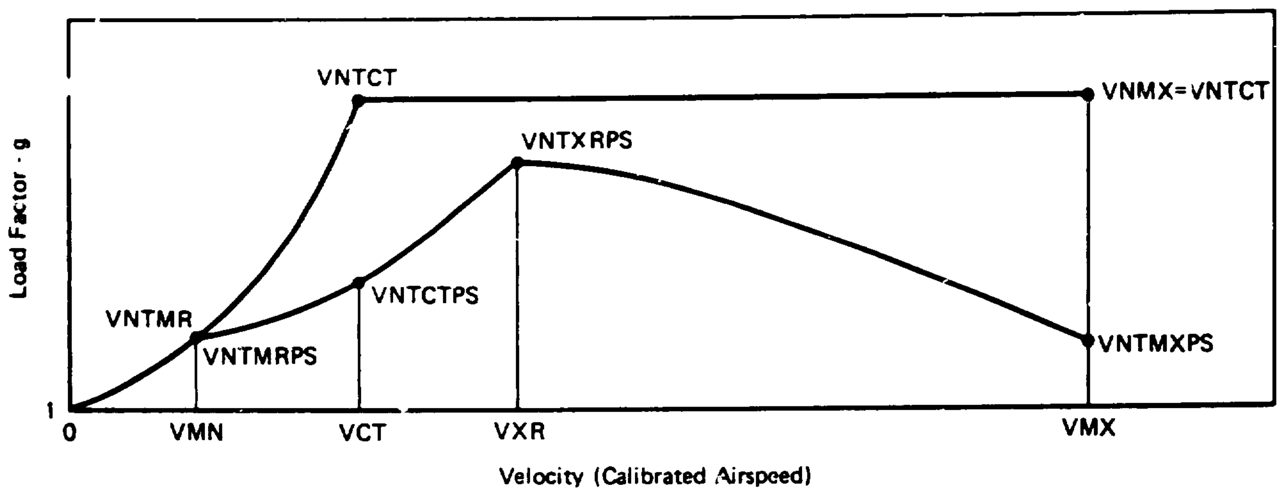


Figure 8. Display Data Point Definition, V-N Diagram

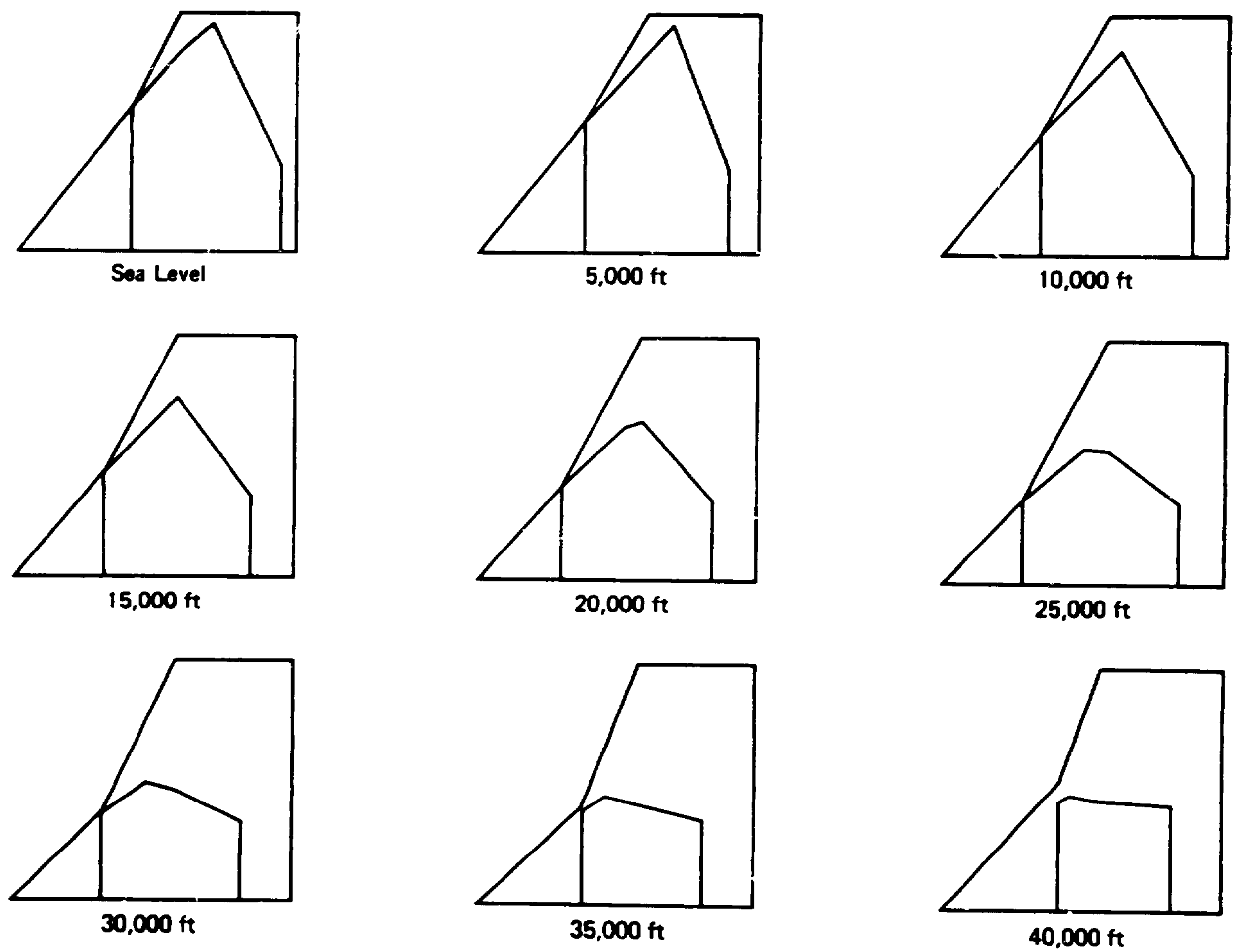


Figure 9. V-N Diagram F-4
GS = 41,500 lb
Vertical Scale = 260
Horizontal Scale = 300

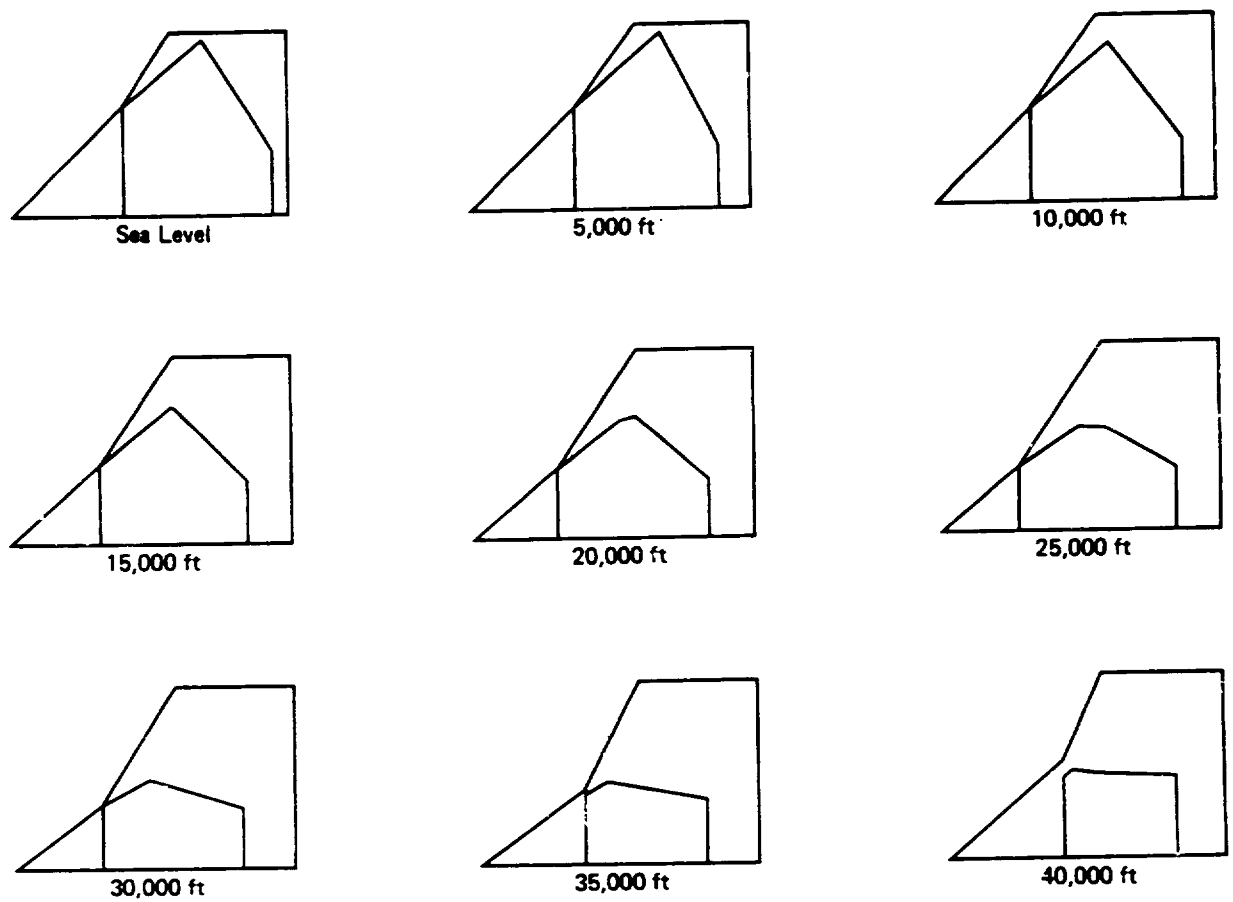


Figure 10. V-N Diagram F-4
GS = 41.500 lb
Vertical Scale = 200
Horizontal Scale = 300

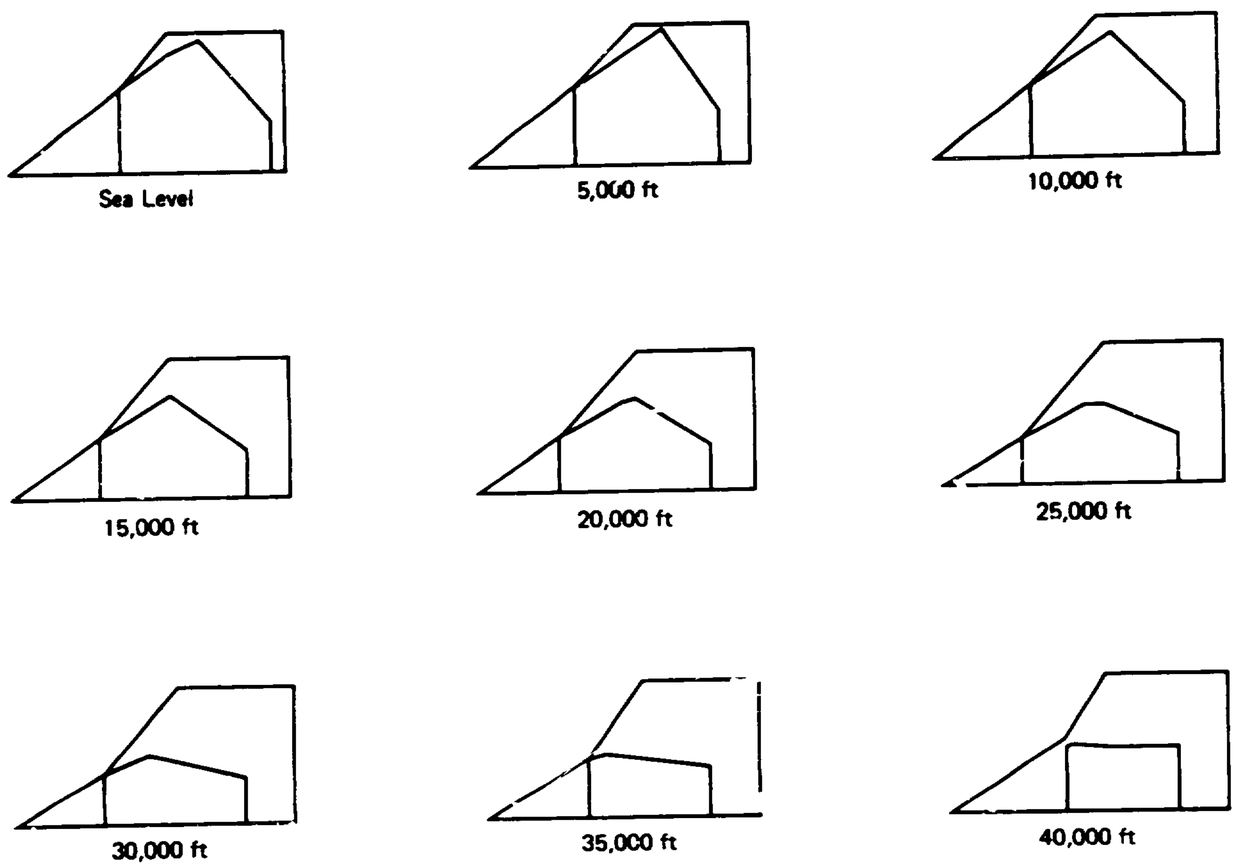
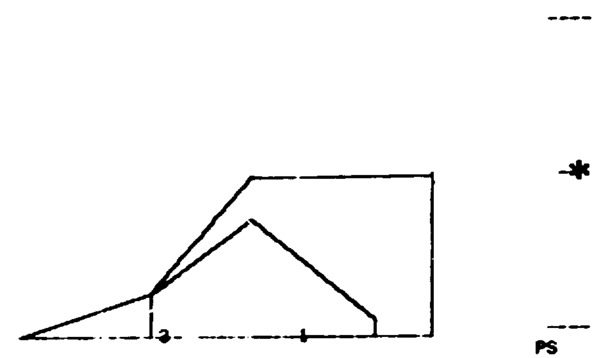


Figure 11. V-N Diagram F-4
GS = 41.500 lb
Vertical Scale = 150
Horizontal Scale = 300

901120080Y 01/12/79 1533:45:37* REPLAY ON-LINE MODE 5

EMD2
1/3



A/C	1	2	3	4
ALT	15432	0	15626	
TAS	692	0	351	
IAS	517	0	278	
MACH	1.10	.00	.55	
AOA	11	5	18	
G	5.0	.0	2.5	
	0	101PU	0	
FILT	5	6	7	

Figure 12. DDS GRAPHICS
V-N Format

2.4 ACMR EM DISPLAY

During the initial portion of this program both the basic Maneuver Triangle and V-N display were mechanized. The preliminary verification of the entry data tables, algorithms, and scale factors was made by generating the display format shown in Figures 13(a), (b), (c), (d), and (e). (EMD-1 represents the maneuver triangle and EMD-2 the V-N display.)

The symbol "0" represents the turn rate-speed position of the simulated aircraft within the maneuver triangle. Three potentiometers on the DDS control panel were used to manually select altitude, "g", and velocity representing aircraft inputs. Various altitudes, speeds, and "g" were selected and hardcopy prints similar to those shown in Figure 13 were made. Data points used to generate the display and the present position indicator were manually scaled and calculated using the hardcopy print. Any discrepancies found were corrected using this technique throughout the complete altitude, speed, and load factor range. Verification consisted of comparing the display values to table input values and calculated input values.

Once the data had been verified, this portion of the software program was removed and the displays were implemented to operate with an ACMR replay tape. The present position indicator displays the aircraft's current position within the envelope. Its operation was verified using selected maneuvers from an F-4 one vs one engagement. Appendix B provides additional detail on the present position indicator.

The replay tape was stopped at several positions throughout the engagement. Each time the tape was stopped, the "Engineering Data" display was called up. The downlinked and computed display data were compared to the data on the EM display. Unfortunately, the ACMR complex does not have the facilities to print a hardcopy of a data time history. Verification of data was performed by manually scaling data off the display and comparing the scaled data with the 'engineering display' data. To allow for the impact of weight changes on P_s, it was necessary to provide corrections for the EM displays. The nature of these corrections is specified in Appendix C. Turn rates were considered acceptable if within 1.0^{o}/sec and velocity within 5 KTS. This verification was performed on tapes where the fuel quantity was known from pilot reports. (Range conditions during this period of time did not permit an F-4 to fly specific profiles for subsequent verification.) Based on the scaling performed, it was concluded that the EM displays reflect correct F-4 performance.

After the displays were verified to display correct data, they were shown to pilots at NAS Miramar to obtain comments.

Pilots from the Navy Fighter Weapons School (TOP GUN) provided valuable assistance in providing operationally usable displays. An initial critique from TOP GUN indicated that since aircraft comparisons are made on the basis of turn rate and velocity, that format would be superior to the V-N display for training purposes. Since the turn rate-velocity method is now being used by the Navy to develop tactics,

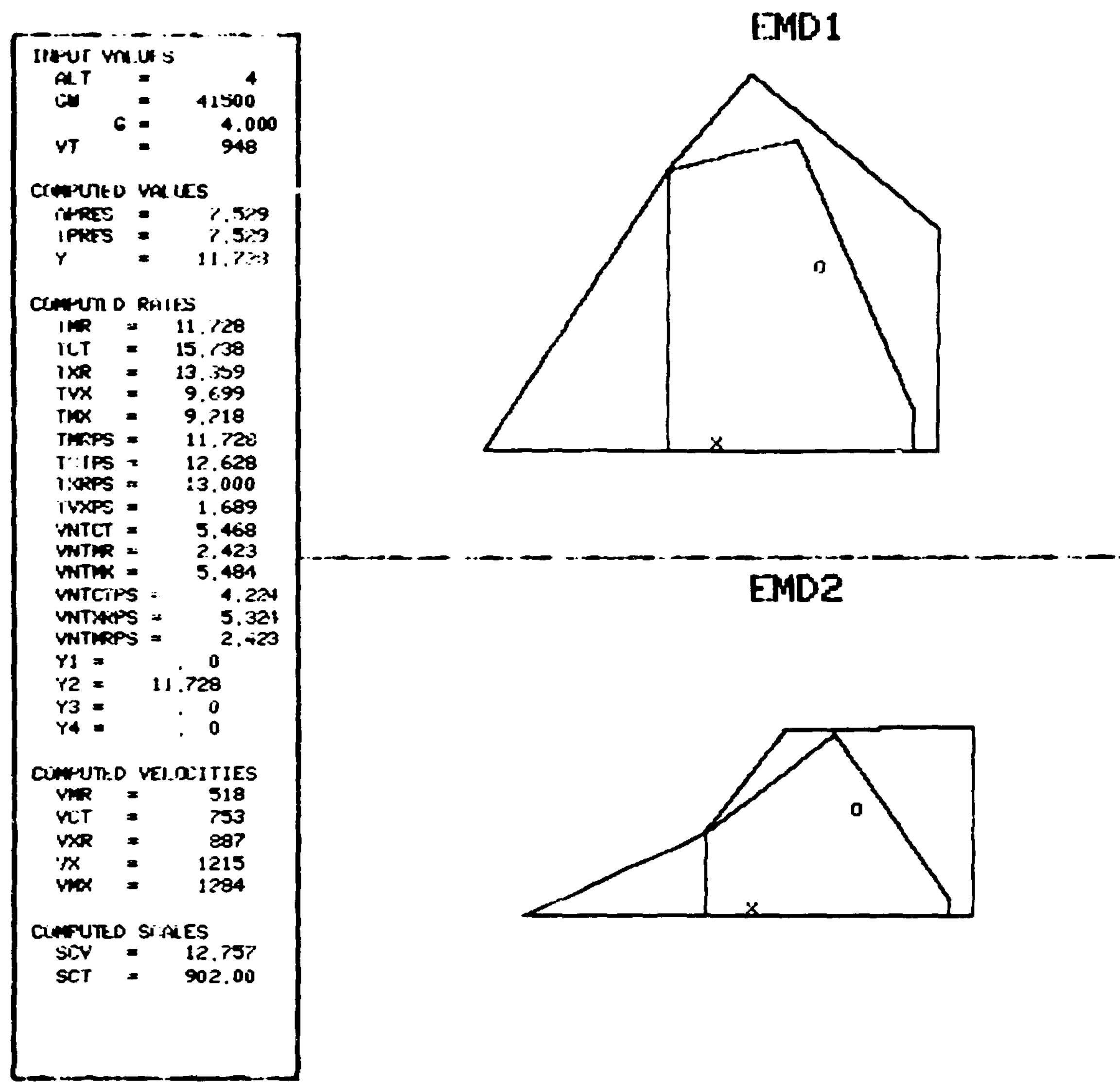


Figure 13(a). Display Format Verification, Sea Level

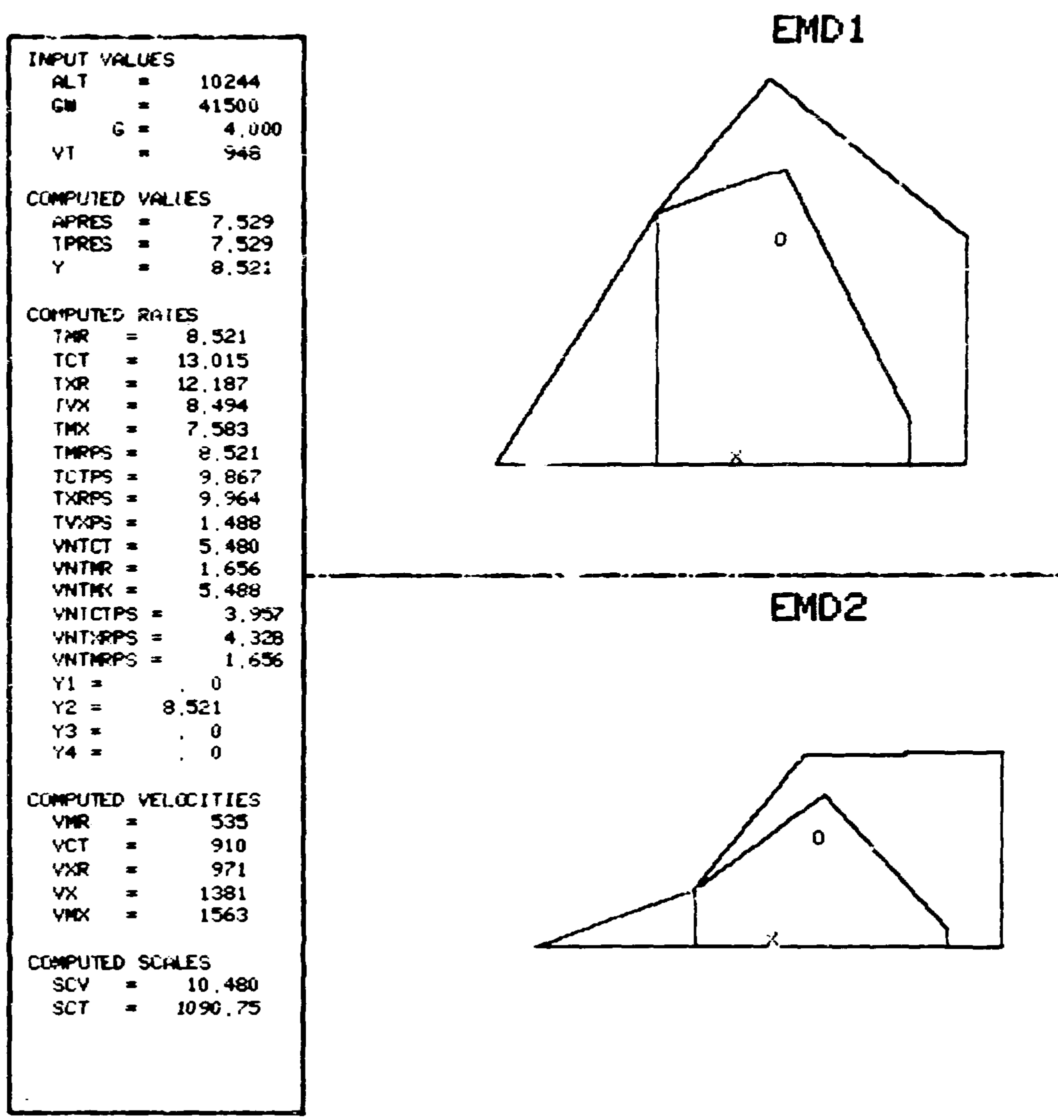


Figure 13(b). Display Format Verification, Altitude 10,000 ft

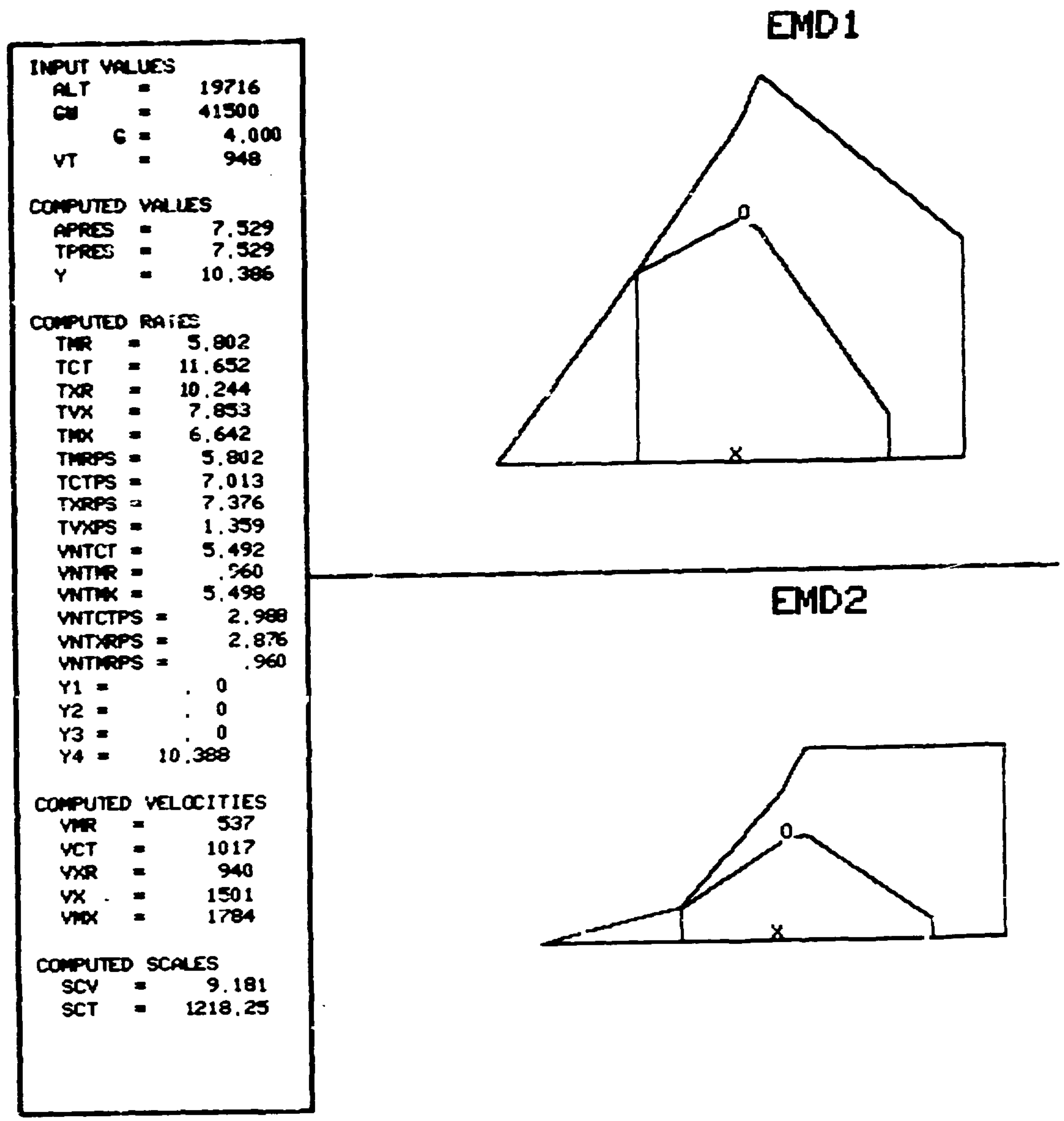


Figure 13(c). Display Format Verification, Altitude 20,000 ft

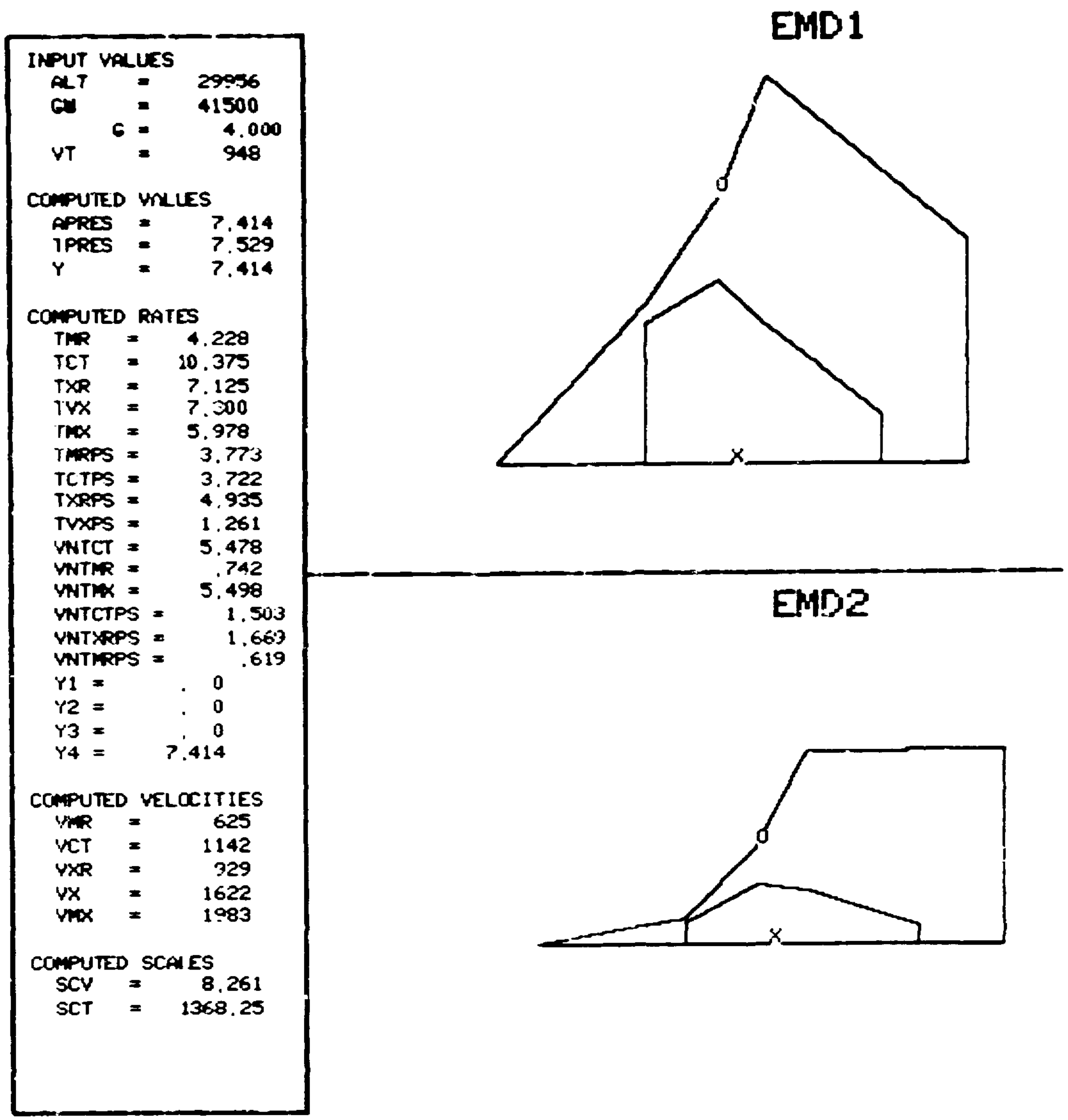


Figura 13(d). Display Format Verification, Altitude 30,000 ft

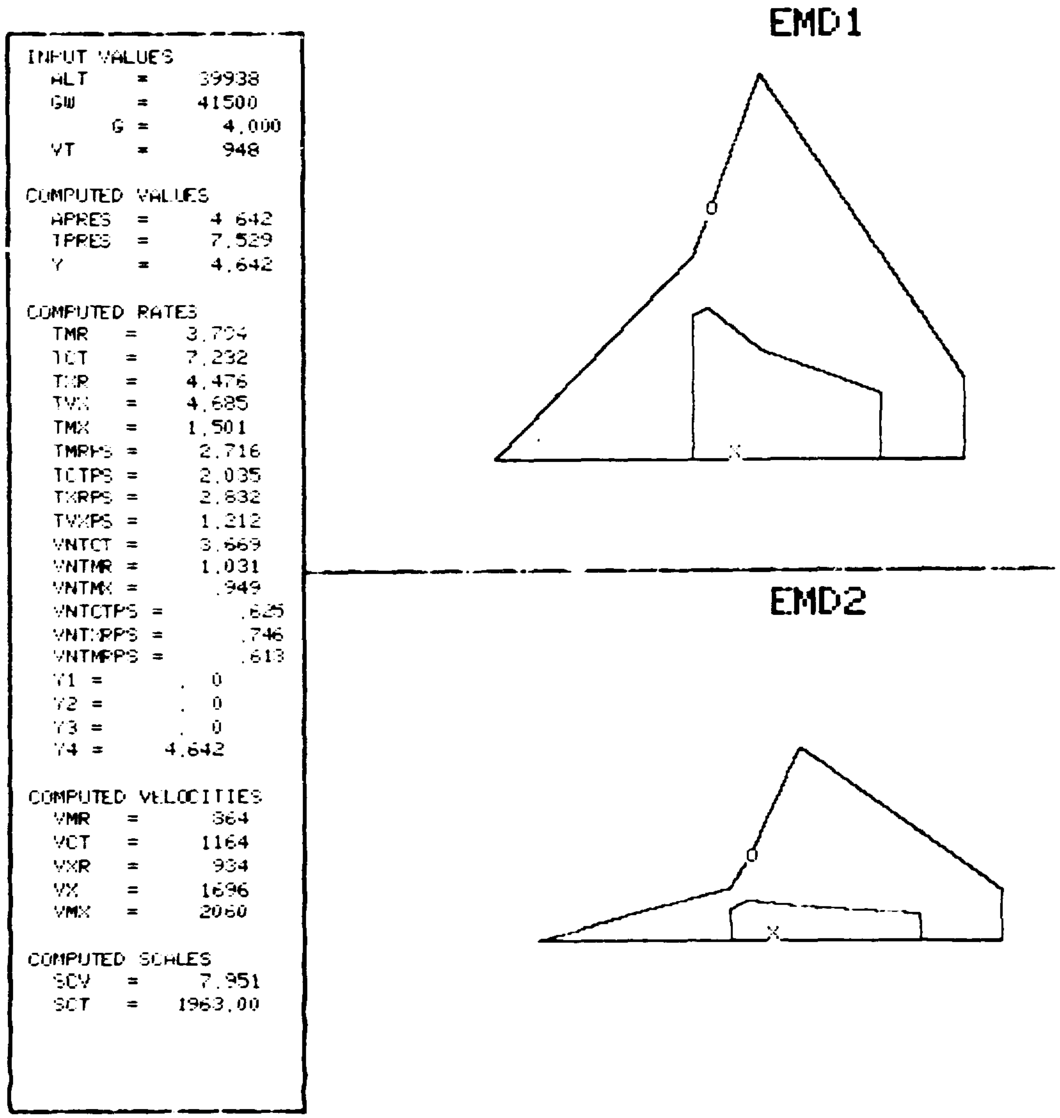


Figure 13(e). Display Format Verification, Altitude 40,000 ft

TOP GUN indicated that it would be desirable to show the turn-rate displays for both aircraft on the ACMR display. By having the maneuver triangle for each aircraft, debrief crews could observe how each pilot was using his energy to counter moves by the other.

Navy pilots recommended that the base scales be changed to indicate 750 KCAS as a maximum. As a result of this change, data are calculated in true airspeed, then converted to calibrated airspeed for display. Vertical scaling was also changed.

These changes resulted in the display shown in Figure 14. The sea level table of the corner turn for each aircraft is used to establish which of the two competing aircraft has the highest turn rate. This value is then used as the vertical scale for both aircraft. The display for each aircraft is then scaled based upon this value. The small numbers on the display portray the aircraft's current state within its maneuvering envelope. By observing both displays in the horizontal plane, it becomes an easy task to determine which aircraft has the turn rate advantage and how each pilot is using his performance and energy for the situation. Also, the data portrayed are now the same as the data used in the classroom.

It was also quickly learned that the maneuver triangle must be in conjunction with the 3-D display to obtain the most benefit from the ACMR debrief. The 3-D display is used to determine relative positioning, while the EM display is used to observe maneuvering potential. The addition of the EM display often shows dynamically why mistakes are made.

During the verification phase, it was proposed that the two EM displays be integrated, the figures overlaid, and the data below the figure be rescaled. An illustration of the alternate display is contained in Figure 15. The solid line outlines the maneuvering triangle of aircraft 3, while the dashed line outlines the maneuvering triangle of aircraft 4. Aircraft 3 and aircraft 4 are dissimilar types. An examination of Figure 15 will reveal that aircraft 4 is in an area of energy loss, below corner velocity, losing altitude, but maintaining constant velocity by trading altitude for airspeed. Aircraft 3 is in an area of energy gain, slightly below corner velocity, in a slight climb, and maintaining a constant velocity. It can be noted from the figure that for the altitudes indicated (approximately 23 Kft), aircraft 4 has a considerably higher $C_{L_{max}}$ than aircraft 3, a lower corner velocity (CV) than aircraft 3 and a turn rate approximately twice that of aircraft 3. Assuming a tactical situation, in which aircraft 3 and aircraft 4 are commencing a turn toward each other, then if aircraft 4 attempts to turn toward aircraft 3, aircraft 4 will very rapidly lose energy and be forced to fight at a lower airspeed. It should be noted that due to aircraft 4's higher $C_{L_{max}}$, aircraft 4 will have a substantially smaller turning radius at the lower airspeed. Alternately, if aircraft 3 remains in the area of energy gain, he may accelerate to CV and when tactically appropriate, he may turn at his CV. It would be unwise for aircraft 3 to engage aircraft 4 at less than approximately 450 KTS (aircraft 3's CV). Alternately, if aircraft 3 dives to gain airspeed, aircraft 4 could then use its better turning capabilities at the lower altitudes.

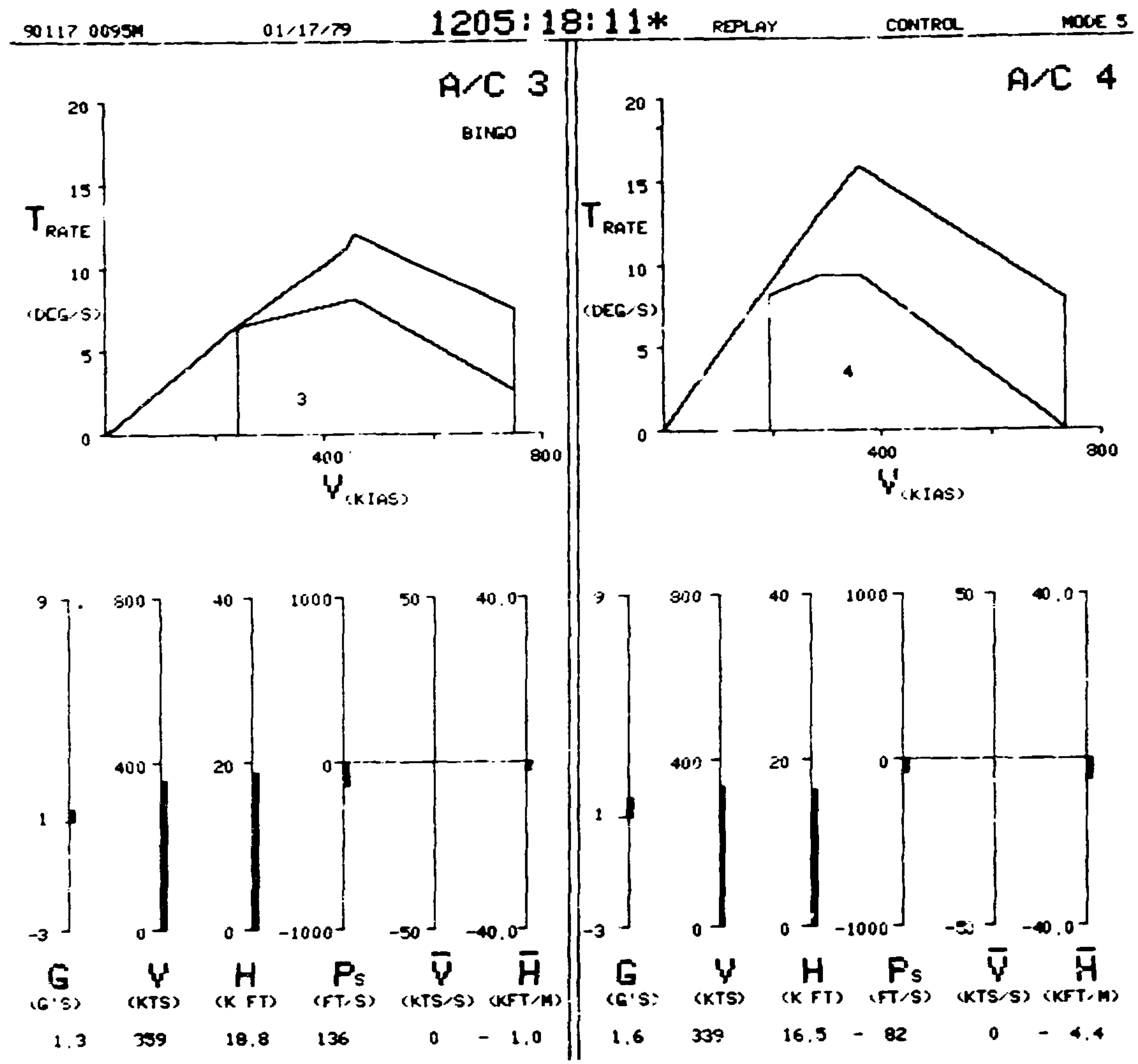


Figure 14. DDS Graphics
EM Display Format

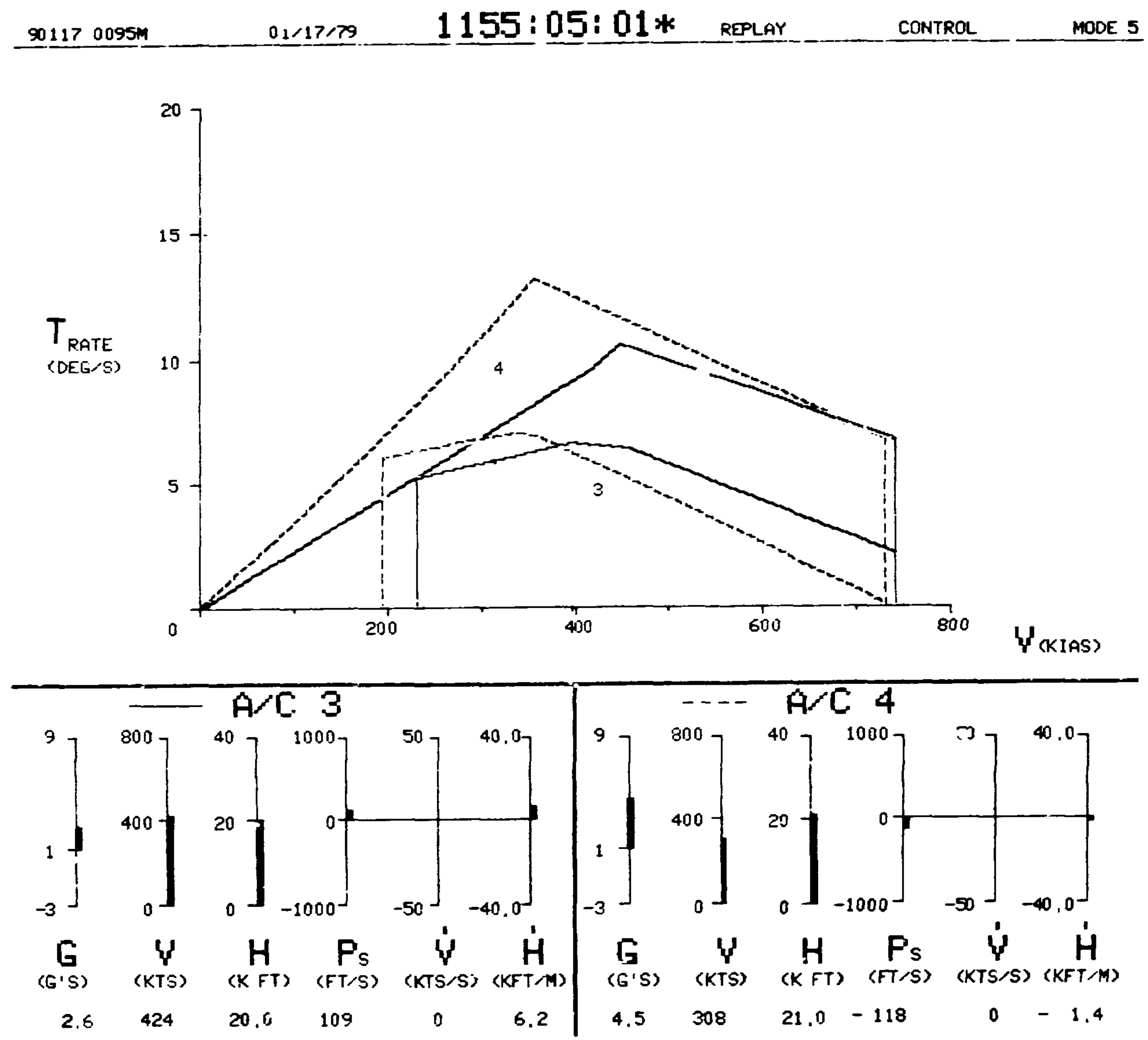


Figure 15. DDS GRAPHICS
EM Display Format (Alternate)

Figure 15 is based on dissimilar aircraft types. Presently, data are available at the ACMR which will allow comparisons of not only the F-4 but the F-14, F-5, and A-4 against similar or dissimilar aircraft types.

2.5 VIDEO TAPE PRESENTATION

With the availability of the new EM displays at the West Coast ACMR, at least two video tapes will be made to serve as training and briefing supplements. The first tape will be a short summary, lasting about 15 minutes. It will include a short overview on energy management and dissimilar aircraft comparison. Following the overview will be a nontechnical description of the EM displays, followed by a sample of a debrief using a short engagement segment.

The second tape being made will be 60-90 minutes long. This tape can be used for training and refreshers by squadrons using the ACMR. The first part of the tape will cover the "energy management" and "aircraft comparison" lectures, presently given by TOP GUN. Added to this will be a debrief session, covering display usage and including an actual analysis of a one-vs-one engagement on the ACMR.

III. CONCLUSIONS

Based on preliminary indications, incorporation of the EM displays into the ACMR should enhance ACM training. The display format proposed was acceptable to both flight crews and the evaluating pilots of the Naval Fighter Weapons School (NFWS), who indicated that the displays should become part of the Navy training as soon as possible. The Commanding Officer, NFWS (8) stated, "The Energy Maneuverability Display on the ACMR represents a large step forward in the understanding of EM concepts by fleet fighter aircrews and its effect on air-to-air tactics."

Commander Naval Air Systems Command (AIR 06E) has requested (9) that the display developed under this program be made available for incorporation into the ACMR/TACTS. As requested, the software and documentation have been made available to Commander, Fighter Wings Pacific by the Commander, Pacific Missile Test Center (10).

It should be noted that the EM display is designed for qualitative use and should not be used for detailed quantitative performance assessment. The method of approximating weight and fuel used is adequate only for qualitative usage.

IV. RECOMMENDATIONS

Recommendations are listed below:

1. The alternate display format, Figure 15, should be implemented to replace Figure 14.

2. An evaluation of the effectiveness of the display and video tapes should be performed.

3. The display and associated video tapes need to be formally integrated into ACMR/TACTS training and performance evaluation program.

4. A concerted effort should be made to obtain more information on weight and fuel flow, to determine the overall accuracy of the weight approximation.

5. Consideration should be given to incorporating EM displays at other ACMR/ACMI. At these other facilities, the use of multicolor displays may enhance the overlay technique.

6. Consideration should be given to incorporating EM displays into ACM trainers such as the F-14 Air Combat Maneuvering Simulator and the USAF Simulator for the Air-to-Air Combat.

V. REFERENCES

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5. Moroney, W. F., and Barnette, J. F., Development of a helmet mounted light emitting diode display and its application as an energy maneuverability display. Pt. Mugu, CA.: Pacific Missile Test Center. In preparation 1980.

6. Stanley, R., Limited flight evaluation of a helmet-mounted tactical maneuvering display system on the NT-38A aircraft. Report SY-115R-79. Patuxent River, MD.: Naval Air Test Center, November 1979.

7. Pruitt, V. R., Energy management display system for a tactical fighter (U) (Confidential). AAFDL-TR-73-38. Wright-Patterson AFB: USAF Flight Dynamics Laboratory, April 1973.

8. Commanding Officer, Navy Fighter Weapons School letter of 7 May, 1979. Evaluation of energy maneuverability display (EMD); Incorporation into the Air Combat Maneuvering Range (ACMR).

9. COMNAVAIRSYSCOM MSG 040805Z, January 1980, ACMR/TACTS Energy Maneuverability Program.

10. COMPACMISTESTCEN letter of 20 March 1980, Ser A385 to NAVAIRSYSCOM 06E, 340F, and 413. Subject: Energy Maneuverability Program: Transfer of Documentation for. SSIC #1226/3960.

APPENDIX A

ENERGY MANEUVERABILITY AND DISPLAY CONCEPT BACKGROUND

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ENERGY MANEUVERABILITY AND DISPLAY CONCEPT BACKGROUND

From practical experience the fighter pilot knows that maneuverability is a function of speed, altitude, and the aircraft's capability to change speed or altitude. Since energy maneuverability is referred to in terms of energy and energy rate, it is helpful to look at the mathematical expressions for both.

- Energy. For the sake of simplicity, the expression for total energy (the sum of potential and kinetic energy) is divided by weight to give an expression for specific energy (E_s). Thus,

$$E_s = (V^2/2g) + h \tag{1}$$

E_s = Specific energy (ft)

V = Velocity (ft/sec)

g = Gravitational constant (ft/sec^2)

h = Altitude (ft)

- Energy Rate. Energy rate is the time derivative of specific energy; i.e., a measure of the amount by which specific energy is changing or can be changed per second. This is normally expressed as:

$$\dot{E} = \frac{V\dot{V}}{g} + \dot{h} \tag{2}$$

where

$\dot{E}$ = Energy rate (ft/sec)

V = Velocity (ft/sec)

$\dot{V}$ = Acceleration (ft/sec^2)

$\dot{h}$ = Altitude rate of change (ft/sec)

In describing aircraft performance energy rate is more commonly expressed as:

$$\dot{E} = \frac{T-D}{W} V \tag{3}$$

where

$\dot{E}$ = Energy rate (ft/sec)

T = Thrust available (lbs)

D = Total drag (lbs)

W = Aircraft weight (lbs)

V = Velocity (ft/sec)

When expressed in this way energy rate is commonly referred to as P_s or specific excess power. Equation (3) is derived by first summing the forces about the aircraft's center of gravity. The forces can be expressed as

$$F = T - D - W\sin T = Ma \qquad (4)$$

where

F = Force (lbs)

T = Thrust (lbs)

D = Drag (lbs)

W = Weight (lbs)

T = Aircraft flight path angle

M = Mass ($Slugs/ft^3$)

a = Acceleration (ft/sec^2)

Solving for (a) in equation (4) and substituting it for $\dot{V}$ in equation (2)

$$\dot{E} = \frac{V}{g}\ \frac{g}{W}\ (T - D - W\sin T\ ) + V\sin T$$

where

$V\sin T = \dot{h}$

and simplifying

$$\frac{V\ \ (T-D-W\sin T)}{W} + V\sin T = \frac{V(T-D)}{W}$$

Therefore,

$$\dot{E} = \frac{T-D}{W} \quad V = P_s$$

It is the expression for P_s that provides insight into energy maneuverability concepts. With the arithmetic sign and the value of P_s, the ability of an aircraft to climb, accelerate, decelerate, and turn can be determined. Assuming a constant maximum thrust at constant weight for a given altitude, the controlling variable is drag. Drag at zero lift (parasite and wave drag) is a function of Mach, altitude, and external configuration. Of these, the pilot has direct control over external store configuration through his jettisoning system. Induced drag (drag due to lift) is also a function of Mach, altitude and, more importantly, load factor. The pilot exercises load factor control through stick position. The pilot, therefore, can exercise substantial control over his specific excess power. The relationship between P_s and maneuverability can be viewed as follows.

If the angle-of-attack is increased from the zero-lift point (pilot increases back pressure on the stick), the normal load factor ("g") will increase, causing a corresponding rise in induced drag which adds to the zero-lift drag. This increased drag (see equation 3) reduces the excess thrust available. If the angle-of-attack is increased to a point where the drag equals the thrust ($T-D = 0$ or $P_s = 0$), a steady state condition exists. Up to the $P_s = 0$ point, a positive P_s exists; therefore, energy can be gained and P_s becomes a measure of acceleration at constant altitude, rate of climb at constant velocity or a combination of acceleration, turn and climb capability. At $P_s = 0$, the normal load factor becomes sustainable.

A further increase in angle-of-attack correspondingly increases induced drag until the drag is greater than thrust. This results in a negative energy rate and becomes a measure of deceleration, loss of altitude, or both. The angle-of-attack can be increased either to the aerodynamic limit of the aircraft (the point of maximum lift, or a limit of controllability, or to its maximum structural limit. Since these limits define the aircraft's maneuvering envelop, it is common to show them on a V-N diagram (Figure A-1). The shape of this envelope changes with altitude, but generally speaking, the maximum load factor ("g"s) is determined at low speeds by the aerodynamic limit and at high speeds by the structural limit.

Of specific importance in discussing maneuverability is the cornor turn. The corner turn occurs where the aerodynamic limit intersects the structural limit. It is referred to as the corner turn because it is the point at which the aircraft can achieve its maximum turn rate at nearly its minimum turn radius. This can be more clearly seen by referring to Figure A-2, where lines of constant turn rate and turn radius have been superimposed on the V-N diagram. The significant point of this V-N diagram is the fact that turn radius reaches a near minimum while turn rate approaches a maximum as the corner turn is approached. This particular diagram shows the $P_s = 0$ boundary intersecting the maximum-"g" boundary. It should be noted that this occurs only on high thrust-to-weight (T/W) ratio aircraft at low altitude. On most aircraft, the P_s=0 boundary begins to drop (reduced "g"s) rapidly as airspeed increases after reaching a maximum. (Remember that thrust is greater at low altitude and drag increases with airspeed and load factor.)

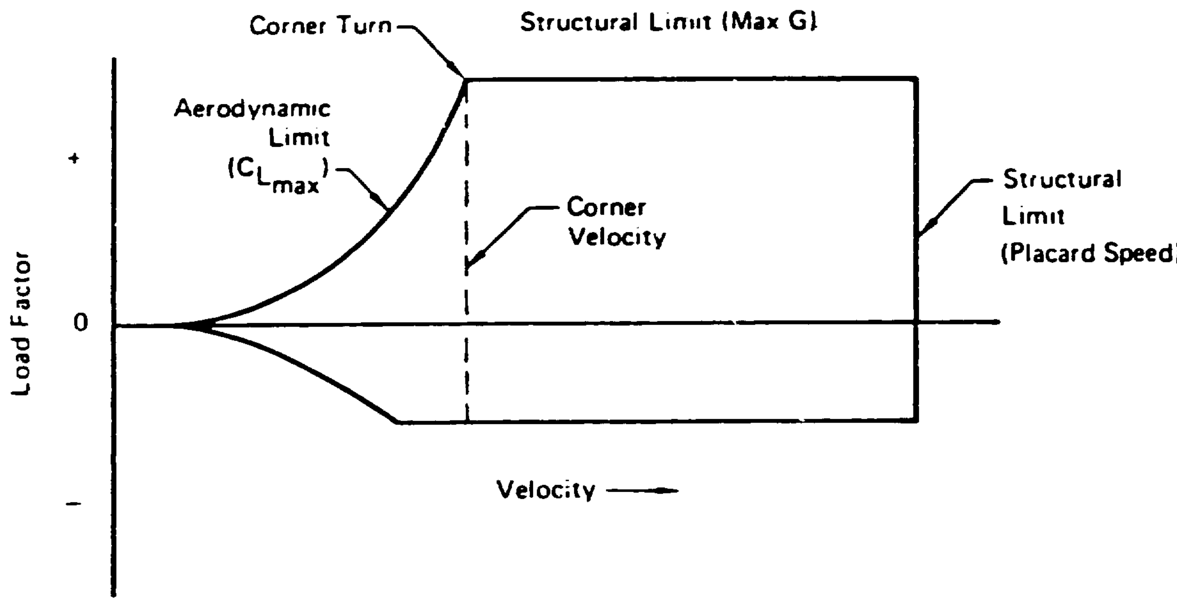

Figure A-1. Basic V-N Diagram

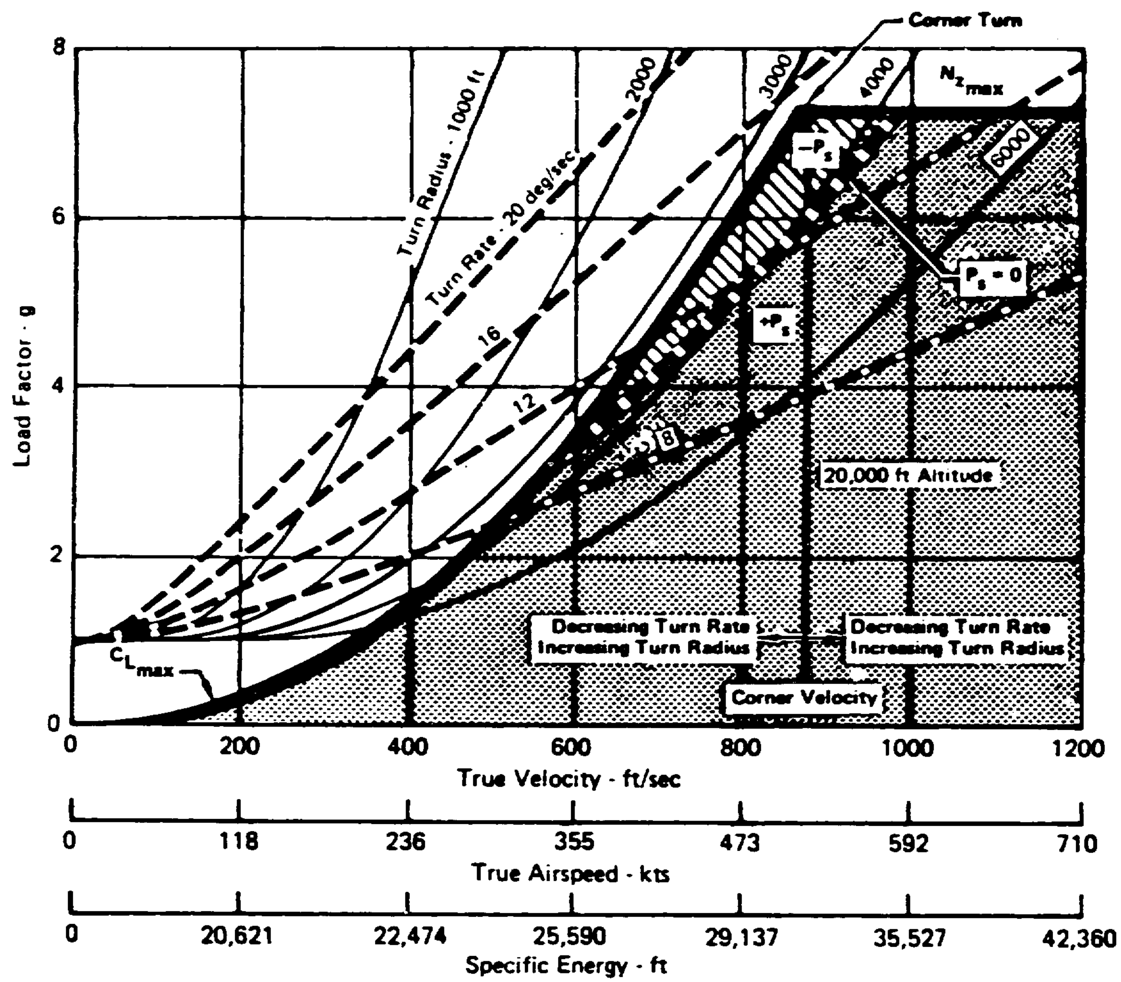

Figure A-2. V-N Diagram

Since the ability to "out-turn" the adversary is important, this aspect will be discussed. To evaluate the turning performance of an aircraft it is convenient to construct rate-radius profiles for various altitudes, as shown in Figure A-3. Several aircraft characteristics important to maneuvering combat are highlighted by rate-radius profiles, namely;

1. The absolute maximum instantaneous turn rate occurs at low altitude (sea level).

2. The maximum turn rate for any given altitude occurs at the corner turn.

3. The near minimum turn radius (at low to medium altitudes) occurs near the corner turn.

4. For each altitude the area above the dashed line (the $P_s = 0$ value) represents an area of energy loss or negative P_s. The dotted line itself is a zero P_s line on which a turn can be sustained. Below the line is an area of energy gain.

5. The maximum sustained turn rate occurs where the dashed $P_s = 0$ line is at a maximum.

An important property of maximum turn rates is their sensitivity to both altitude and airspeed, the two determinants of specific energy. It should be noted that the best turning capability does not occur at the highest energy level. Another significant point is that when the aircraft is pulling maximum load factor, turn radius increases and turn rate decreases with increasing airspeed. This fact is an extremely significant consideration for aircraft with high thrust to weight ratios. Pilots of these high performance aircraft must learn that to increase turn rate and decrease turn radius, it may be necessary to reduce power - - an act that most fighter pilots are clearly unaccustomed to. A pilot must learn to reduce power until he enters an area of negative P_s before power can be advanced. If the pilot does not reduce power when in a positive P_s region, he will continue to climb at maximum sustained load factor until the altitude for max "g" at max power is attained. (The aircraft will gain energy in terms of both altitude and airspeed until the thrust becomes equal to drag). As demonstrated by the rate-radius profile, a pilot with positive P_s who fails to reduce airspeed will inadvertently reduce turn rate and increase turn radius, thus forfeiting his superior performance.

A previous study* explored the combat requirements for a suitable energy management display. Concepts of energy maneuverability were reduced to bare essentials to arrive at a simple display to enhance pilot proficiency.

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*Pruitt, V. R., Within Visual Range Energy Management Display. Report MDC-A 3504. St. Louis, Mo.: McDonnell Aircraft Company, October, 1974.

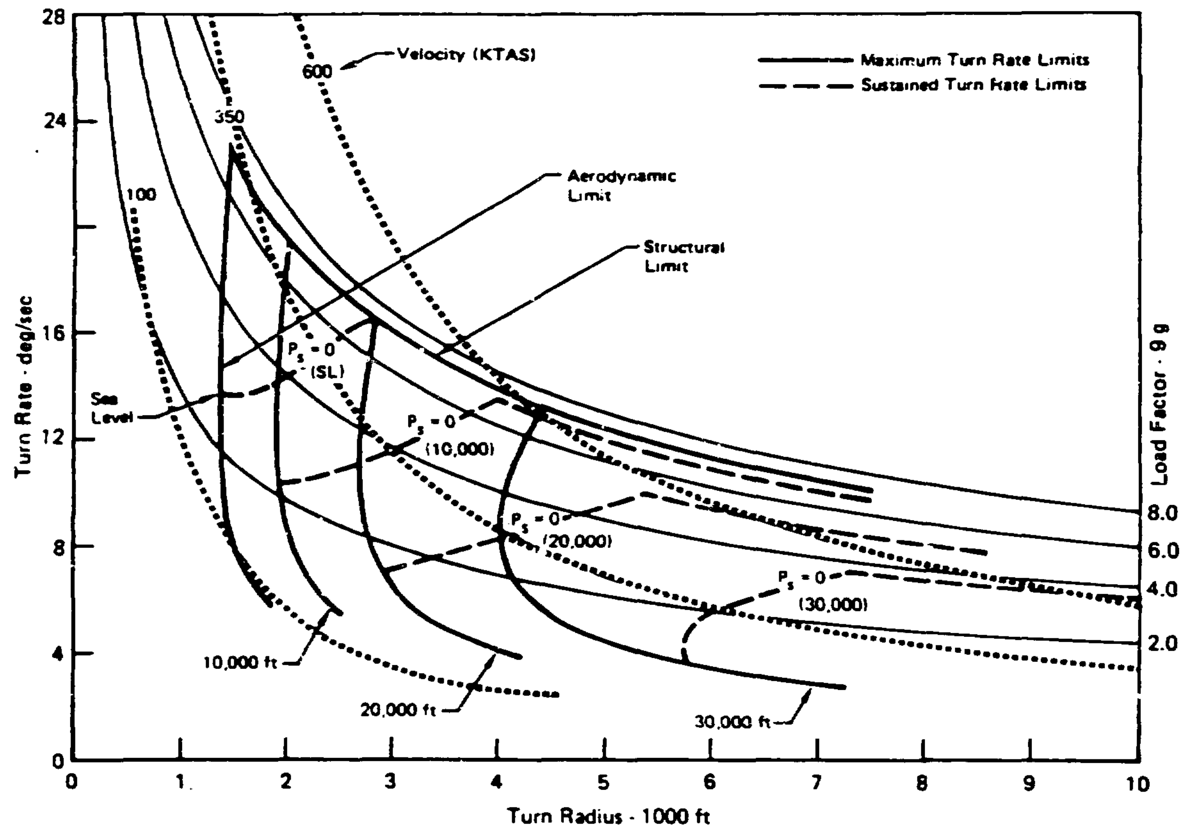


Figure A-3. Typical Rate Radius Profile

Having established that key maneuver parameters were more easily understood when defined as a function of Maneuver Potential (N_z/V) and Velocity, the maneuver envelopes were converted to a velocity-maneuver potential plot as seen in Figure A-4. The key points of interest are shown:

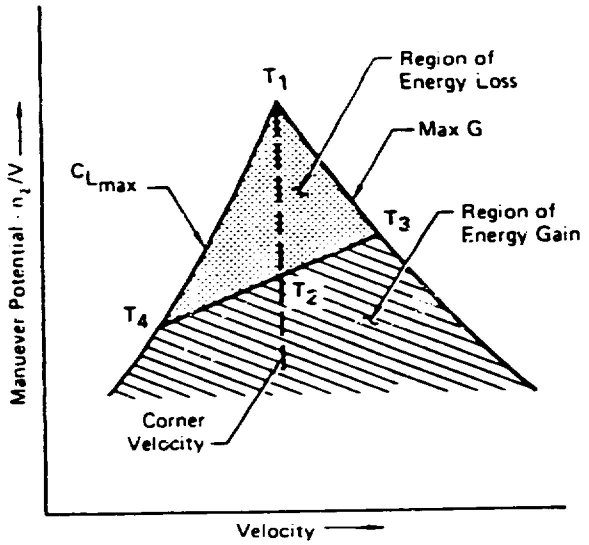
- The point T_1 represents the quickest-tightest turn. This point has been previously defined as the corner turn condition and occurs at the intersection of the maximum lift and maximum structural limit boundary. The rate-radius profile (Figure A-3) indicates clearly the maximum turn rate and near-minimum turn radius at this condition.

- The point T_2 represents the Steady State Turn at the Corner Velocity. This is the point where the corner velocity intersects the $P_s = 0$ line and is characterized by a thrust equal to drag and a speed at which the quickest-tightest turn is available if needed. The line (T_1 to T_2) is the equivalent of the verticle line on the V-N diagram at the corner velocity.

- The point T_3 represents the Maximum Steady State Turn. At this point thrust and drag are balanced with maximum load factor available. At low altitudes, a power reduction may be required to maintain this turn.

- Point T_4 represents the Minimum Sustained Turn Radius. This point is defined by the intersection of the zero specific excess power curve and the maximum lift boundary. Turns at speeds below this point are sustainable at maximum power for low thrust to weight ratio aircraft. For high thrust to weight ratio aircraft, speeds below the minimum sustained turn radius velocity will result in an energy gain at maximum power.

The Maneuver Triangle concept (Figure A-5) was derived from these key turning parameters. The base of the triangle represents energy level or velocity from zero to V_{max} for the corresponding altitude. The left leg of the triangle represents the maximum lift boundary and the right leg represents the maximum load factor. For a given velocity, either the left or right leg boundary, as appropriate, represents the maximum instantaneous maneuver potential. Information on sustained maneuvering potential is provided by a line from the left boundary to the right boundary representing zero specific excess power ($P_s = 0$). The maximum sustained maneuver performance occurs where this line forms a peak. The shaded area above the sustained maneuver potential line (Figure A-6) represents an area of negative P_s or energy loss. The area below the sustained maneuver potential line represents an area of energy gain or positive P_s. The circle represents the aircraft's current position within the aircraft's potential maneuver envelope.



T1 Quickest - Tightest Turn
- Maximum Rate of Turn
- Near Minimum Turn Radius
- Airplane Decelerating

T2 Steady State Turn at the Corner Velocity
- Maximum Instantaneous Turn Capability Available
- Thrust, Drag are Balanced

T3 Steady State Maximum Rate of Turn
- Maximum Sustainable Rate of Turn
- Maximum Load Factor
- Thrust, Drag are Balanced

T4 Steady State Minimum Radius of Turn
- Minimum Sustainable Turn Radius
- Thrust, Drag are Balanced

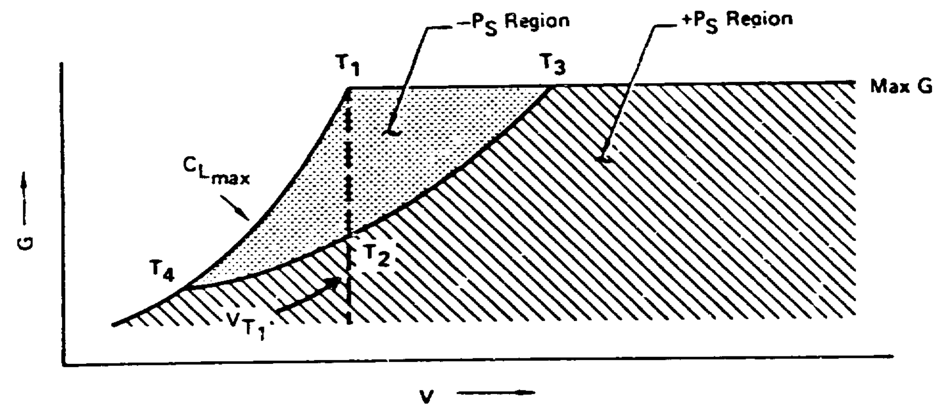


Figure A-4. Key Maneuver Conditions

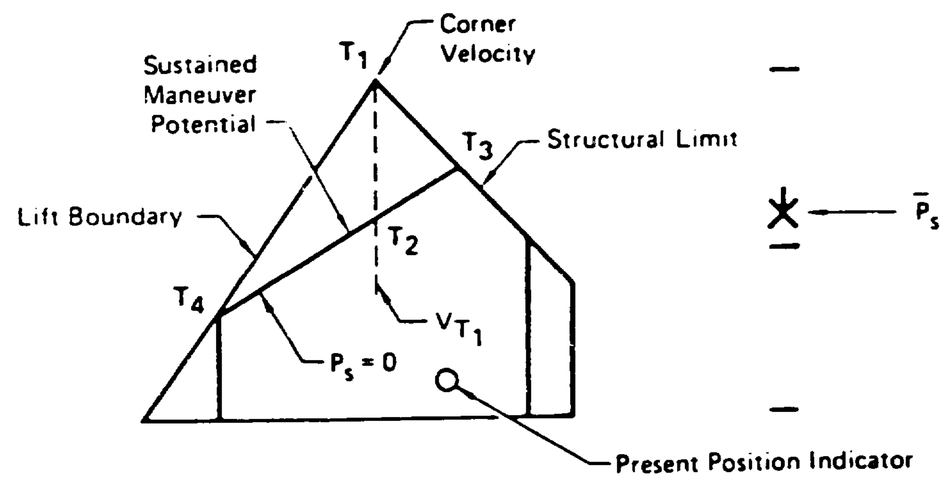


Figure A-5. Maneuver Triangle

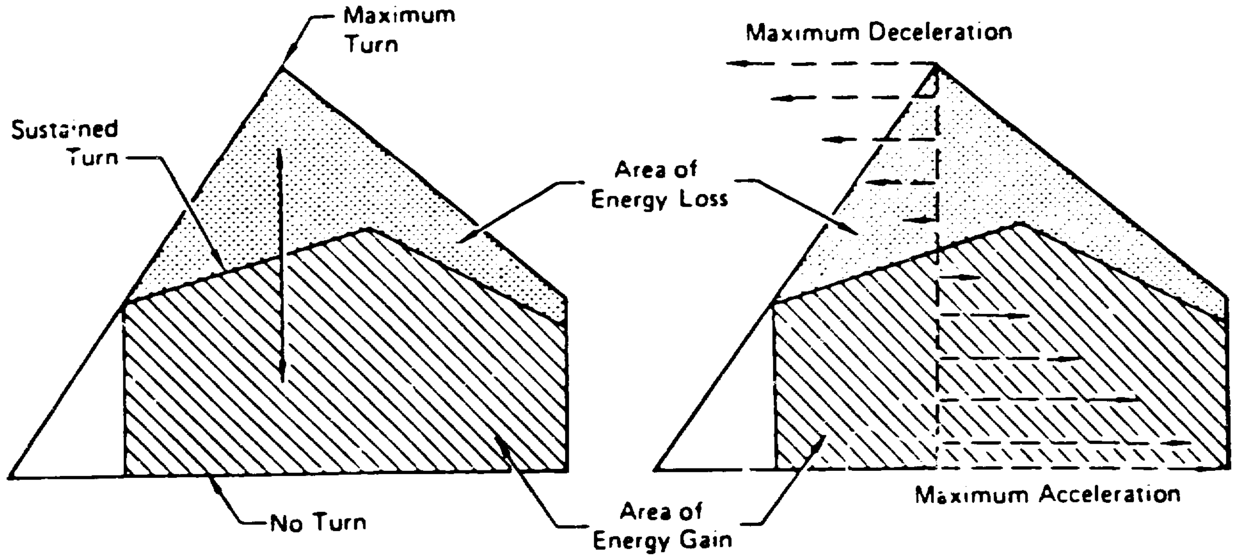


Figure A-6. Maneuver Triangle Trends

APPENDIX B

PRESENT POSITION INDICATOR

APPENDIX B

PRESENT POSITION INDICATOR

A present position indicator displays the aircraft's current position within its turn rate-velocity envelope. This indicator is prevented from exceeding the $C_{L_{max}}$ boundary by comparing the present turn rate with the interpolated $C_{L_{max}}$ boundary turn rate. Even though the aircraft can remain airborne outside the $C_{L_{max}}$ boundary (for example during slow speed over-the-top maneuvers), MCAIR pilots recommended that the display limit be established, to avoid confusion. The present position indicator is, however, allowed to exceed the specified maximum "g" limit.

For the F-4, a maximum value of 6.5 "g"s was used. If the aircraft exceeds 6.5 "g"s the present position indicator indicates the actual rate on the display above the $N_{z_{max}}$ limit line. The base has been calculated so that any time the aircraft is less than 1.1 "g"s, the turn rate is set to zero.

On the ACMR display, the center of the numeric character representing the aircraft is the current turn rate-velocity location.

APPENDIX C

CORRECTIONS FOR CHANGES IN GROSS WEIGHT

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CORRECTIONS FOR CHANGES IN GROSS WEIGHT

Recalling that the expression for specific excess power is

$$P_s = \frac{T - D}{W} V,$$

it can be seen that weight is a significant variable. Due to the change in weight as fuel burns, it is necessary to provide corrections for the EM displays. Two methods were considered. The first was to enter data for at least three weights, and interpolate the data, causing the display to shift slightly as fuel is burned. Figure C-1 shows display shifts for an F-4 at three fuel weights: 25 percent, 50 percent, and 75 percent of on-range fuel. On-range fuel is the total fuel estimated for use while on the ACMR range for a particular aircraft.

The second method is to correct the present position indicator to reflect weight change. The second method was chosen, to reduce the number of tables necessary for all potential future aircraft using the ACMR. Details are discussed below.

Unfortunately, neither gross weight nor fuel quantities is available through the ACMR downlink. Therefore, a method of approximating fuel weight was developed. Table C-I shows the values that are used as basic input weights. The empty weight is the operating weight empty of an F-4J. The Navy defined typical F-4 configurations that are used on the ACMR. Both are equipped with one AIM 9 and one AID Pod. The difference between the two entries for each location is the centerline tank. Therefore, the weight of 2 pylons and LAU-7A launchers and 2 AIM-9 missiles was added to the empty weight, as shown on the table. The AID Pod was assumed to have the same weight and aerodynamic characteristics as the AIM-9.

The "on-range" fuel was supplied by the NFWS as the average fuel on board when arriving at the West Coast ACMR from Miramar or Yuma. Also supplied was the BINGO fuel necessary to return to Miramar or Yuma. The difference between the on-range fuel and the BINGO fuel is the fuel available for ACM.

Since data need to be provided for only one weight, the 50 percent point was chosen. One half of the fuel available for ACM was added to the Bingo fuel state and the empty weight to determine the "50 percent display gross weight." All data tables used for display mechanization were constructed using these weights.

The present position indicator on the EM display is corrected by multiplying the aircraft current turn rate by a weight ratio:

$$\text{WTRATO} = \frac{\text{PRESENT WEIGHT}}{\text{50\% DISPLAY GROSS WEIGHT}}$$

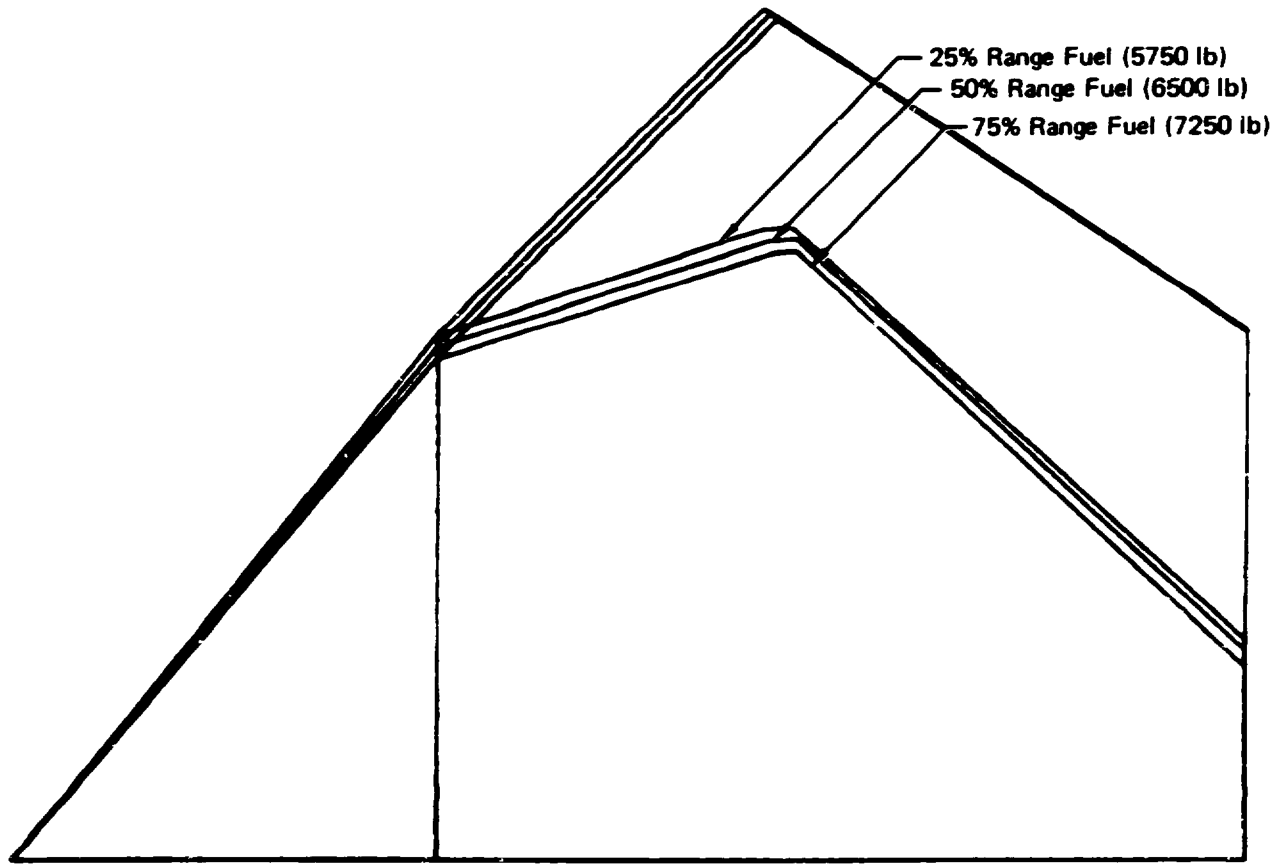

Figure C-1. EMD Comparison for Three Fuel States
F-4 15,000 ft Altitude (Miramar)

Table C-I

	Miramar		Yuma	
	No Tanks	℄ Tank	No Tanks	℄ Tank
Empty Weight	32,107	32,411	32,107	32,411
Pylons and 2 AIM-9s	652	652	652	652
	32,759	33,063	32,759	33,063
On Range Fuel	8,000	11,000	11,500	13,000
Bingo	5,000	5,000	2,500	2,500
Fuel Available	3,000	6,000	9,000	10,500
50% Fuel Available	1,500	3,000	4,500	5,020
+ Bingo	5,000	5,000	2,500	2,500
50% Fuel Onboard	6,500	8,000	7,000	7,520
Gross Weight	39,259	41,063	39,759	40,583

If the aircraft is lighter than 50 percent display gross weight, the present position indicator is corrected downward. If the aircraft is heavier, the turn rate is adjusted upward.

The next step was to devise a method of approximating current fuel weights. ACMR range times were provided by the NFWS, and the average was determined to be about eight minutes. During those eight minutes, the allowable range fuel will be consumed. For each location and configuration, an average fuel flow was calculated. Logic within the ACMR Control and Computation Subsystem (CCS) "knows" when the using aircraft crosses the range boundaries. As the aircraft crosses the range boundaries, the average calculated fuel flow is used to correct the fuel-on-board estimate. (When the ACMR starts using serial data concepts, using the aircraft MUX BUS to supply data, actual fuel weight will be available.)

Only two fuel checks were obtained from F-4's during this study. However, they agreed very closely to the approximation method of calculating fuel. One fuel check occurred at 6400 pounds. Data at the time of the fuel check indicated a weight ratio of 0.9785. This ratio yields a fuel weight of 5655 pounds, or 733 pounds lower than reported.

The weight ratio at 6400 pounds would be 0.9974. The difference, representing the 733 pounds, is 0.0189. At an actual turn rate of 10 deg/sec, this introduced an error in the present position indicator of 0.189 deg/sec.

The second fuel check obtained occurred at 4600 pounds. The weight ratio being calculated when this state was reported equals 0.0953. The weight ratio for 4600 pounds is 0.9516. The difference is 0.0063.

Figure C-2 represents the displayed turn rate as a function of weight error. As mentioned previously, at the present time there is no way to obtain these fuel differences. If it is assumed that the fuel weight will never be much more than 1000 pounds in error, then the maximum display error at 20 deg/sec would be 0.5 deg/sec. Since the present position character has a height representing approximately 0.8 deg/sec, it is felt that for qualitative assessment, the 0.5 deg/sec error at a 20 deg/sec turn is acceptable.

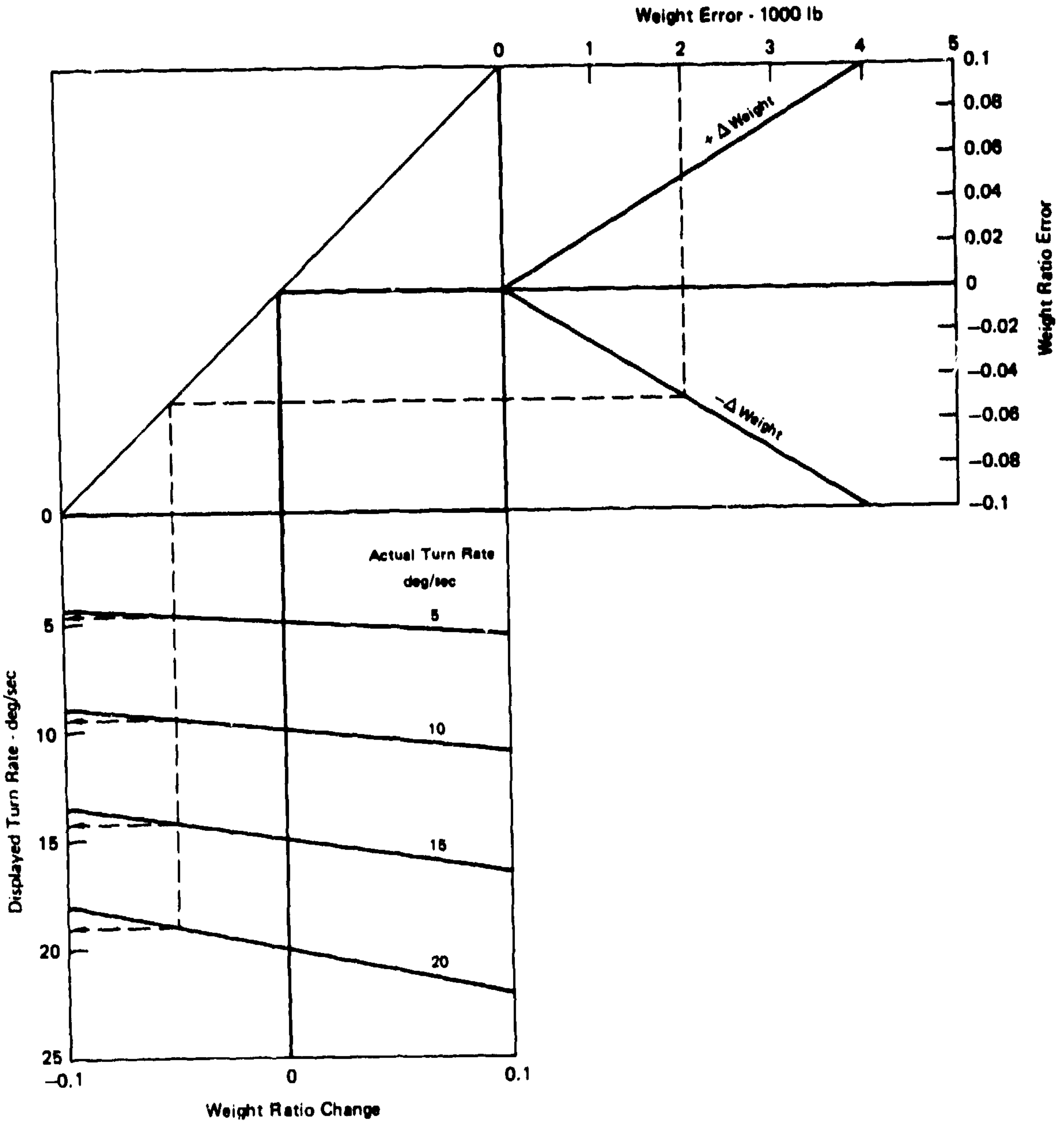

Figure C-2. Display Turn Rate Error
F-4 50 percent Range Fuel
EW = 32,107 lb

APPENDIX D

CONDITIONING OF ACMR DATA

APPENDIX D

CONDITIONING OF ACMR DATA

The data being received by the ACMR and used for display generation are: ALTITUDE, AIRSPEED, and LOAD FACTOR. The Maximum Standard Deviation error is shown in Table D-I.

Table D-I

DATA SPECIFICATIONS

Parameter	Limitations	Maximum Standard Deviation Error	
		Specification	Measured
ALTITUDE	5000 - 50000 ft	25 ft	25 ft
MACH	250 ft/sec - Mach 1.6	0.02M	0.02M
VELOCITY COMPONENTS	250 ft/sec - Mach 1.6	15 ft/sec	5 ft/sec
LOAD FACTOR	-2.5 to 8.5 "g"	0.5 "g"	0.05 "g"

DATA CONDITIONING

Data samples on the ACMR are obtained 10 times/sec. However, several of the parameters used on the EM displays become very "jumpy" if updated on the display at 10 times/sec. In order to remove this jumpiness, smoothing routines are used on both velocity and load factor. A stack of 10 frames of data (1 sec) is established, then averaged. This average value is used for display. Each 100 ms, the new value is added to the stack and the oldest value is removed. This type of smoothing provides a steady input to the display and still allows display refresh at 100-ms intervals.

Load factor is used for the calculation of turn rate and display of the present position indicator. The "g" value being displayed on the lower portion of the display (bar chart and alphanumeric) is not processed through the smoothing routine.

The smoothed velocity is used only for the calculations of $\dot{E}$, V, and P_s. All other velocity inputs are not affected by the smoothing routines.

P_s is calculated by computing the total specific energy at two times, separated by 100 ms. Energy rate is the difference in the total specific energy for the 100-ms time interval. P_s is calculated as the rate of change of specific energy,

where:

$$E_S = h + \frac{V^2}{2g}$$

and:

$$P_s = E_{S_1} - E_{S_2}$$

$\dot{V}$ is simply the velocity difference over one-second time period, yielding acceleration. $\dot{H}$ is the rate of change of altitude, and is calculated directly from ACMR input data. It should be noted that since the DDS could not generate an easily visible dot required for the $\dot{V}$ and $\dot{H}$ symbols, a line was drawn in place of the dot.

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Over the past decade, emphasis has been placed on designing fighter aircraft to energy maneuverability criteria. These criteria have indeed increased fighter performance, but they have also presented analysts and pilots with new tasks in fully utilizing this improved capability. In the development of tactics, the energy maneuverability capability of a potential adversary's aircraft must be compared with the maneuvering capability of one's own aircraft. A major factor which deter-

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mines the outcome of aerial combat is the pilot's ability to maximize the maneuvering capability of his aircraft. This report describes the development of an integrated analog display (turn rate vs calibrated airspeed) for use as a debriefing aid on the Air Combat Maneuvering Range (ACMR).

The ACMR gathers in-flight data from aircraft while they are engaged in air combat maneuvering. Upon returning from the ACMR, aircrew are presented with 1) a pictorial display of the engagement, and 2) a digital printout of selected encounter paramaters (e.g., velocity, "g", altitude of each aircraft, range between aircraft). The display integrates these relevant energy maneuverability data into an analog format, thus providing an immediate comparison of the performance of each aircraft with respect to the maneuvering envelope of that aircraft and that of the opponent. The display also allows the aircrew to recognize very rapidly whether they are gaining or loosing energy and the rate of gain or loss. The maneuvering envelopes of the F-14, F-4, A-4, and F-5 aircraft can be displayed in this dynamic format. It is expected that this new format 1) will provide a better means for pilots to determine how well they have maximized the performance of their aircraft, and 2) may serve as an aid in tactics development.

A brief discussion of the nature of energy maneuverability is contained in an Appendix.

It is proposed that the effectiveness of the energy maneuverability (EM) display and the companion instructional video tape should be evaluated. The potential incorporation of the display into other ACMRs/ACMIs and ACM simulators should also be considered.